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EXPERIMENTAL EVALUATION ON THE PERFORMANCE OF WASTE BIOMASS BRIQUETTES FORMATION AND COMBUSTION CHARACTERISTICS

LAW HOON CHIT

Thesis submitted in fulfillment of the requirements
for the award of the degree of
Master of Science

Faculty of Mechanical Engineering

UNIVERSITI MALAYSIA PAHANG

SEPTEMBER 2017

ACKNOWLEDGEMENTS

First and foremost, I would like to express my deepest appreciation to all those who provided me the possibility to complete this master degree research. This project would not have been possible without generous assistance, cooperation and support of a number of people.

A special gratitude goes to my supervisor, Dr. Gan Leong Ming, who contributed significantly in stimulating suggestions, continuous encouragement, valuable guidance and advices. His professional supervision and support truly help the progression and smoothness of my project in which his co-operation is highly appreciated.

My sincere appreciation goes to my lab mates, Ms. Gan Hui Leng and Mr. Teo Sir Hiang for their continuous support. Besides, a million thanks to Prof. Dato' Dr. Rosli Abu Bakar, Prof. Ir. Dr. Hassan Bin Ibrahim, Dr Azri Bin Alias, Dr. Ftwi Yohaness Hagos, Dr Chuan Zun Liang, Mr. Lim Syh Kai in sharing knowledge and ideas generously and giving me helping hands to resolve my doubts in research jobs. Also, I would like to convey my gratefulness to laboratory assistants, Mr. Nizam and Mr Jamiluddin for the guidance in using the testing equipment.

Last but not least, I acknowledge my sincere indebtedness and gratitude to my lovely family for their continuous support, encouragement and sacrifice throughout my life. A special thanks to my parents who consistently encouraged me to pursue my studies to a higher education level as well as with their mental and physical support, their tolerance of my ignorance and naïve mistakes.

ABSTRAK

Pada abad kedua puluh, tenaga biojisim telah mendapat perhatian besar bagi sisa biojisim diiktiraf sebagai pembawa tenaga yang boleh diperbaharui dan menguntungkan. Malaysia sedang menjalankan amalan pertanian intensif di mana sekitar 150 bilion metrik tan sisa pertanian yang dihasilkan setiap tahun. Sisa-sisa biojisim boleh diproses sebagai sumber tenaga kerana penggunaannya tidak akan mengganggu amalan pertanian tradisional atau menggugat keselamatan makanan, tetapi sebaliknya meningkatkan lagi kegunaannya. Walau bagaimanapun, kepelbagaian pilihan saiz fizikal dan bentuk, komposisi dan kepadatan tenaga di kalangan biojisim pertanian yang berbeza memberi cabaran dalam pengendalian, penyimpanan serta pengangkutan. Oleh itu, process menghasilkan briket dilaksanakan untuk memadatkan sisa-sisa kepada pelet pukal, briket atau kiub yang tinggi kepadatan. Walau bagaimanapun, sesetengah daripada sisa-sisa tidak boleh dipadatkan dan lain-lain alternatif, contohnya penambahan pengikat atau mencampurkan bahan-bahan biojisim amat diperlukan. Objektif utama kajian ini adalah untuk mengkaji potensi dan bagaimana biojisim yang dipilih boleh digunakan sebagai sumber yang boleh diperbaharui secara berkesan dalam pengeluaran bahan api pepejal. Selain itu, sifat-sifat mekanikal dan pembakaran briket akan disiasat dengan sewajarnya. Dalam kajian ini, sekam padi, tebu hampas dan sisa serbuk kopi dipilih sebagai bahan mentah biojisim untuk pembentukan briket. Sisa-sisa biojisim yang dikumpul dan seterusnya dipotong dalam saiz kecil selepas proses pengeringan. Selepas itu, kemudahan menghasilkan briket yang telah direka khususnya untuk menampung pembentukan briket yang berbentuk donut. Dalam set pertama eksperimen, kesan daripada perubahan suhu pemanasan (120, 150 dan 180°C), tekanan pemadatan (200, 250 dan 300 bar) dan jenis biojisim (sekam padi, tebu hampas dan sisa serbuk kopi) pada rintangan pecah, rintangan lelasan, rintangan air dan rintangan mampatan briket telah disiasat. Rintangan pecah didapati meningkat dengan tekanan dan suhu sekitar 92.09-100%. Rintangan yang kasar meningkat daripada 83.25-90.15% kepada 99.74-99.79% kecuali briket tebu hampas yang stabil pada 100%. Selain itu, 3.26-36.56% daripada kenaikan dicatatkan dalam rintangan air dengan tekanan yang semakin meningkat dan suhu. Rintangan mampatan, selain itu juga meningkat kepada 236.29-1077.78 N. Kajian ini juga menunjukkan bahawa briket tebu hampas menghasilkan kekuatan yang lebih tinggi dibandingkan dengan sekam padi dan briket serbuk kopi bagaimanapun briket kopi menunjukkan keupayaan rintangan air yang tertinggi. Pada set kedua eksperimen, tiga jenis briket biojisim gabungan yang telah dibentuk: sekam padi dan tebu hampas tebu, sekam padi dan sisa serbuk kopi, tebu hampas dan sisa serbuk kopi dengan nisbah campuran 80:20, 60:40, 40:60 dan 20:80. Parameter pemprosesan optimum digunakan dalam eksperimen ini adalah 150°C dan 300 bar. Sifat-sifat mekanik briket gabungan dianalisis berkenaan dengan nisbah campuran. Selain itu, nilai kalori kasar, analisis muktamad dan ujian air didih telah dijalankan untuk menilai prestasi briket. Hasilnya menunjukkan bahawa briket mengandungi sekam padi dan tebu hampas (nisbah berat 20:80), sekam padi dan sisa serbuk kopi (20:80) dan tebu hampas dan sisa serbuk kopi (40:60) mempamerkan kekuatan dan prestasi pembakaran yang dapat memenuhi had penerimaan serta keperluan minimum sebagai briket komersial. Kesimpulannya, keputusan eksperimen mengesahkan keberkesanan kaedah yang digunakan dalam kajian ini dalam process pengeluaran briket biojisim untuk meningkatkan kekuatan mekanikal dan ketahanan serta nilai kalori dan pembakaran kadar briket. Campuran biojisim boleh menjadi penyelesaian alternatif lain bagi industri lain daripada menggunakan hanya satu jenis sisa seperti sisa sawit dan sisa kayu dalam pembentukan bahan api pepejal untuk penjanaan tenaga. Kajian ini itu menyediakan pandangan sifat-sifat mekanik dan pembakaran untuk briket biojisim yang berbeza, menyumbang untuk melanjutkan faedah penggunaan biojisim pertanian untuk meningkatkan penukaran bahan api pepejal.

ABSTRACT

In the twentieth century, biomass energy has received tremendous attention for the waste biomass to be recognised as a renewable and profitable energy carrier. Malaysia is conducting intensive agricultural practices whereby around 150 billion metric tonnes of agricultural wastes are generated annually. This vast amount of biomass residues could be processed as energy source because its use will not only interfere with traditional agricultural practices or jeopardize the food security, but instead further enhances them. However, wide diversity of physical size and shapes, compositions and energy densities among different agricultural biomass posed challenges in handling, storage, feeding as well as transportation. Biomass briquetting therefore is implemented to compact the residues into a high bulk density pellet, briquette or cube by densification. However, some of the residues could not be briquetted and other alternatives, for example, addition of a binder or mixing of biomass materials are required. The main objective of this research is to study the potential and how the selected biomass could be used as a renewable source effectively in solid fuel production. On top of that, the mechanical and combustion properties of the briquettes would be investigated accordingly. In this study, rice husk, sugarcane bagasse and spent coffee ground were chosen as the biomass feedstock for briquette formation. The collected biomass residues were reduced in size after the dehumidification process. After that, the briquetting facility was specifically designed to accommodate the doughnut-shaped briquette formation. In the first set of experiment, the effects of the variation of preheating temperature (120, 150 and 180°C), compacting pressure (200, 250 and 300 bars) and the biomass type (rice husk, sugarcane bagasse and spent coffee ground) on the shatter resistance, abrasive resistance, water resistance and compressive resistance of the densified product were investigated. It was found that the shatter resistance increased with pressure and temperature to around 92.09-100%. The abrasive resistance increased from 83.25-90.15% to 99.74-99.79% except sugarcane bagasse briquette which was stable at 100%. Besides, 3.26-36.56% of increment was recorded in the water resistance with the increasing pressure and temperature. The compressive resistance, on the other hand increased to 236.29 -1077.78 N. The result also showed that the sugarcane bagasse briquettes exhibited higher strength as compared to that of rice husk and spent coffee ground briquettes, however, spent coffee ground briquettes showed the highest water resistance capability. In the second set of experiments, three types of biomass blend briquettes had been formed: rice husk and sugarcane bagasse, rice husk and spent coffee ground, sugarcane bagasse and spent coffee ground with the mixing ratio of 80:20, 60:40, 40:60 and 20:80. The optimum processing parameters used in this experiment were 150°C and 300 bars. The mechanical properties of the blend briquettes were analysed with respect to the blend ratio and the high heating value, ultimate analysis and water boiling test were conducted to evaluate the performance of the briquettes. The result shows that the briquette containing rice husk and sugarcane bagasse (weight ratio 20:80), rice husk and spent coffee ground (20:80) and sugarcane bagasse and spent coffee ground (40:60) exhibits the mechanical strength and combustion performance which can fulfill the acceptance limit as well as the minimum requirement as a commercial briquette. In conclusion, the experimental results verified the effectiveness of methods applied in this research in biomass briquetting to improve the mechanical strength and durability as well as the calorific value and combustion rate of the briquettes. Mixing of biomass can be the other alternative solution for the industry other than using only one type of residues such as palm wastes and wood residues in solid fuel formation for energy generation. This research thus provides the insights of the mechanical and combustion properties for different biomass briquettes, contributing to further benefits of the application of agricultural biomass to enhance solid fuel conversion.

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W_1	Weight of briquette (g) before shattering
W_2	Weight of the briquette (g) after shattering
W_i	Initial weight of sample before tumbling
W_{ii}	Final weight of sample after tumbling.
W_a	Weight of sample before immersion
W_b	Final weight of sample after immersion
m_f	Mass of fuel burnt, kg
E_f	High heating value, kJ/kg
t	Time to boil, s
W_I	Initial volume of water, kg
kg	kilogram
s	second

LIST OF ABBREVIATIONS

ASTM	American Society of Testing Materials
C	Carbon
CFSP	Chinese Fir and Sewage Sludge
CSP	Camphor and Sewage Sludge
CO_2	Carbon dioxide
GHG	Greenhouse gas
H	Hydrogen
HHV	High Heating Value
HTU	Hydrothermal Liquefaction
N	Nitrogen
NO_x	Nitogen Oxides
S	Sulphur
SO_X	Sulphur Dioxides
SOP	Standard Operating Procedure
SREP	Small Renewable Energy Programme
WBT	Water Boiling Test

CHAPTER 1

INTRODUCTION

1.1 Background of Study

The utilisation of fossil fuels has resulted in the anthropogenic greenhouse gas (GHG), especially carbon dioxide (CO_2) emissions and consequently threatening the environment as well as future human society's development (Wang et al., 2017). As reported by Garrett-Peltier (2017), the global carbon emissions have come to an unsustainable level, and therefore the global energy system must be transformed in order to limit global climate change to a 2°C rise above pre-industrial levels by 2100. Apart from that, impacts from the generation of excessive solid waste annually have alarmed the societies towards the environmental issues due to improper waste management. Therefore, development of sustainable energy conversion system based on renewable sources is essential to secure economic and social development in the future.

According to Dermibas (2009), biomass appears to be the world's fourth largest energy source after coal, crude oil and natural gas due to its sustainable supply and ability to mitigate the GHG emissions. Agricultural wastes have been targeted as the potential renewable source worldwide, especially in the countries with intensive agricultural practices which includes Malaysia. Missagia et al. (2011) revealed that the use of agricultural biomass as renewable energy feedstocks is favoured for its use will not threaten the food security or impede the traditional agricultural practices. However, agricultural biomass are commonly available in loose, dispersed and bulky form, which directly contribute to the problems of high moisture content, irregularity in shape and size as well as low bulk density which may pose challenges in handling, storage, transportation and utilisation as a fuel (Kaliyan and Morey, 2009).

These challenges could be upgraded through the process of densification in order to expand the use of biomass in energy generation. With the application of pressure and temperature, the loose and bulky residues are compacted to form a uniform sized and shaped pellets, briquettes, cubes and etc. A quality densified fuel with adequate strength and durability is preferred as to ease the subsequent processes such as handling, storage, and feeding. Nevertheless, there are few factors which are claimed to have effect on the quality of the densified products to be considered (Kaliyan and Morey, 2009), for instance moisture content, compacting pressure, preheating temperature as well as mixing of biomass materials.

Mixing of biomass materials is beneficial in the enhancement of strength and durability of the densified product (Kaliyan and Morey, 2009). Muazu and Stegmann (2015) mentioned that there are problems with the usage of briquettes formed from the pure materials, thus mixing of rice husk and corn cob has been done to raise the fuel quality. In addition, the physical characteristics of rice straw briquettes are proved to be enhanced by using sawdust as binder (Rahaman and Salam, 2017). As a result, the application of an appropriate technology or process is essential in this research, including the determination of preheating temperature, compacting pressure as well as biomass mixing ratio so that the biomass residues can be used effectively as energy source for solid fuel production.

1.2 Problem Statement

As revealed by Liu et al. (2013), direct combustion of raw biomass for heat generation is not an ideal option owing to the inherent properties of the biomass feedstocks such as high moisture and oxygen contents, and high alkaline earth metal content. Wide diversity of physical shapes, compositions and energy densities among different biomass poses serious challenge in transportation, storage and sizing of feedstocks. In order to enhance the biomass utilisation efficiency, biomass briquetting is considered as one of the best alternatives to improve the characteristics of biomass as a renewable energy resource.

The significance of the biomass densification process has been verified through several research works due to their inherent nature which triggers the problems of handling, feeding, storage and transporting. Nevertheless, there are cases when there is difficulty to form briquettes from the selected biomass. Therefore, addition of binders or mixing of different biomass material is common to improve the binding properties of the particular main residue. In some European countries, addition of binders is prohibited (Kaliyan and Morey, 2009) which will increase the cost of production and impose environmental problems. However, mixing of residues could help to reduce processing cost of briquetting or to achieve a higher abrasion resistance.

The main focus of this research is to investigate the potential of selected residues to be converted into solid fuel for energy generation and their performance in terms of mechanical and combustion properties. On top of that, mixing of the agricultural residues is anticipated to help in production of quality solid fuel since there are certain problems dealing with the briquetting of pure residues. Integration of the densification process and the relevant parameters or variables involved is crucial to process the wastes and transform them into usable combustible materials in which the fossil fuels can be substituted.

1.3 Objectives

In order to address the research problem stated in the previous section, the main aim of this study would be to investigate the potential of selected agricultural residues to be densified into solid fuel for energy generation. The objectives of this project are as follows:

a. To investigate the effect of manipulated compacting pressure and preheating temperature on the mechanical properties of the biomass briquettes produced from agricultural residues.
b. To evaluate the biomass blend briquettes' properties in terms of mechanical and combustion performance.

1.4 Scope of Study

The scope for this project is summarised as follows:

a. Rice husk, sugarcane bagasse and spent coffee ground are chosen as the biomass feedstocks in this study due to their abundant quantity in Malaysia as well as their potential as a renewable source.

b. The grinding speed used for size reduction is from 500-580 rpm, while the particle size of the ground materials is not taken into consideration in this study.

c. For the individual residue, the briquettes are formed with preheating temperature of 120, 150 and 180° C and compacting pressure of 200, 250 and 300 bars, respectively. Selection of these briquetting parameters is explained in detail in section 3.2.

d. For the biomass blending, three different combinations have been formed with the mixing ratio of 80:20, 60:40, 40:60 and 20:80 while the optimum preheating temperature and compacting pressure are kept constant.

e. The analyses on mechanical properties of the briquettes are shatter resistance, water resistance, abrasive resistance and compressive resistance test, dealing to the problem of handling, storing, transporting and feeding.

f. Combustion properties analyses cover energy value determination, ultimate analysis and water boiling test which only apply for the blend briquette together with the selected pure residue briquettes.

1.5 Hypothesis

Biomass briquetting process is anticipated to be an effective method to compact raw biomass into quality solid fuel. The mechanical and combustion properties of the blend briquettes are mapped based on the testing performance. The higher the preheating temperature and compacting pressure, the strength and combustion performance of the densified product would be positively affected. On top of that, the strength and durability of the briquettes could be improved through mixing of biomass materials and it is expected that the blend briquettes can be competitive as compared to the briquette without blend. At the end of the research, it was anticipated that the mechanical and combustion properties of the biomass briquettes can be enhanced through mixing of different material for the materials can complement each other with respect to their strength and weaknesses.

CHAPTER 2

LITERATURE REVIEW

2.1 Potential and Types of Agricultural Biomass in Malaysia

Biomass is defined as any biodegradable organic matter from plant, animal and microbial origin. The agricultural and forestry residues, products or by-products as well as the municipal solid wastes and industrial wastes are examples of the biomass sources (Zubairu and Gana, 2014). As reported by Oladeji (2015), biomass from plants can also serve as an alternative renewable and carbon-neutral raw material for energy generation.

Agricultural wastes have been targeted as the potential energy source worldwide, especially in countries with intensive agricultural practices, resulting in a vast amount of residue production. This particular category of biomass is favoured for its use will not threaten the food security or impede traditional agricultural practices (Missagia et al., 2011). As acknowledged by Chen, Xing and Han (2009), there are additional benefits with the development of biomass energy from agro-residues, for instance it is clean, sustainable and inexhaustible. Besides, this particular development can help to generate rural incomes, accelerate industrialisation of agriculture as well as minimise environmental pollution.

Malaysia is endowed with a wealth of natural resources especially agricultural wastes due to its strategic location and humid tropical climate throughout the year. According to Asim et al. (2015), each year, about 150 billion metric tonnes of agricultural waste are produced. The wastes produced can provide an additional advantage if the excess wastes biomass can be converted into energy sources for biofuel production in the forms of solid, liquid or gas.

The amount of the agricultural wastes produced in Malaysia in 2007 is summarised in Table 2.1 according to Mekhilef et al. (2011). The statistical data reflects the potential of the abundant agricultural residues to be renewable resources that can be recycled or reprocessed for energy generation.

Table 2.1 Production of agricultural biomass in Malaysia

Types of agricultural biomass	Quantity (ktonnes)	Percentage (%)
Oil palm fronds	46,837	50.04
Empty fruit bunches	18,022	19.25
Oil palm fibres	11,059	11.82
Oil palm shells	4,506	4.81
Oil palm trunk	10,827	11.57
Paddy straw	880	0.94
Rice husk	484	0.52
Banana residues	530	0.57
Sugarcane bagasse	234	0.25
Coconut husk	171	0.18
Pineapple waste	48	0.05

Source: Mekhilef, Saidur, Safari, and Mustaffa (2011)

Based on Table 2.1, there is a large quantity of residues produced from the plantation and the figures will increase from year to year. Unfortunately, the common handling methods on these excessive biomass wastes are open burning and disposal to the landfill. Both methods have posed challenge to the farmers and general public for the residues constitute a nuisance to the environment and an eyesore to the public as well (Oladeji, 2015). Instead of practising the open burning and disposal methods for the excessive agricultural residues, these wastes can be used as the energy source for electricity and heat generation.

Besides oil palm wastes, the potential of other types of agricultural residues to be converted into solid fuel will be highlighted in the following sections. The residues are subject to the solid fuel production of this research.

2.1.1 Paddy Residues

In Malaysia, rice is known as a security crop and staple food for major population and also the source of income for farmers from rural areas. There are approximately 150,000 of farmers depending specifically on paddy cultivation for their overall sustenance. Although the average rice productivity level in Malaysia is lower as compared to the world average value, the supply is still sufficient to support the population. The total paddy production had achieved 2.63 million tonnes back in 2013 which were cultivated in 688,207 ha of farmland (Muazu et al., 2015).

As reviewed by Shafie (2016), the paddy is cultivated twice a year in both major season and off season. The major season of paddy plantation focuses in the Northern region of Malaysia, beginning between August and February each year. From the paddy harvesting calendar provided in the official website of Bernas Padiberas Nasional Bhd, one of the local rice producers as shown in Figure 2.1, it can be comprehended that the paddy residues are available over the year in Malaysia. As a result, the current production of paddy residues is up to 1.55 million tonnes in Malaysia per year.

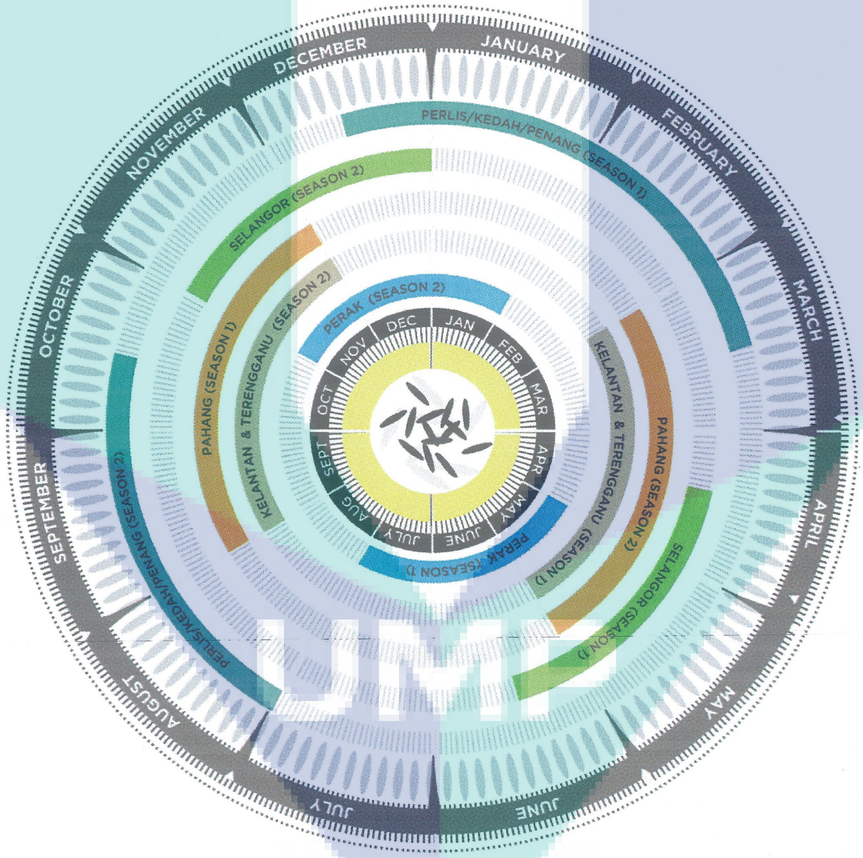


Figure 2.1 Paddy cultivation calendar in Peninsular Malaysia
Source: Bernas Padiberas Nasional Berhad (2016)

Basically, the paddy residues or leftovers (Figure 2.2) from paddy harvesting activities and milling process are composed of rice husk and paddy straw. In Malaysia, paddy residue creates a huge potential to generate electricity at 5652.4 GWh which is equivalent to 5.4% of the total electricity demand among the population (Shafie, 2016).

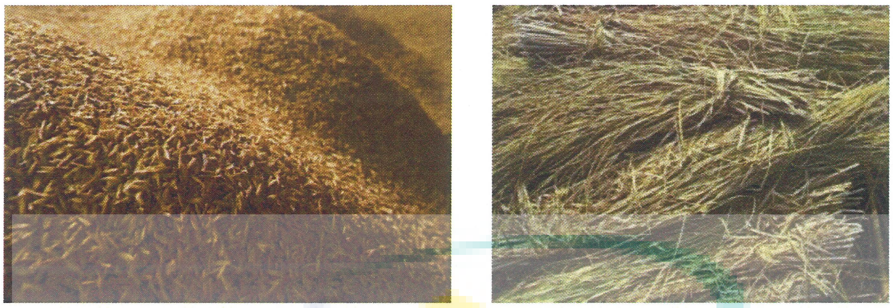


Figure 2.2 Rice husk (left) and paddy straw (right)
Source: Salman (2015)

According to the review paper of Shafie (2016), a total of 231 operating rice mills are available in the whole of Malaysia. There are four rice mills utilising rice husk for electricity generation for their own consumption with the total capacity of 6.18 MW under the Small Renewable Energy Programme (SREP) initiated by the government during the Ninth Malaysia Plan (2006-2010). On top of that, two rice mills located in the northern region of Malaysia consume up to 240 tonnes of rice husk per day to generate a capacity of 700 to 1500 kW of electricity. However, a small portion of the rice husk is still burnt at the road side.

On the contrary, rice straw is normally left in the paddy fields and currently disposed through the method of open burning as a traditional method to make the paddy fields fertile. Yet, a proposal of employing rice straw in the biomass energy plants to generate 12 MW capacity of electricity is still on the drawing board, not being implemented in Malaysia nor in neighbouring countries in Southeast Asia.

Research has been conducted to utilise the paddy residues as the feedstock for solid fuel such as briquettes or pellets production due to their several outstanding benefits. The suitability of the rice husk to be processed into a combustible fuel is due to its low moisture content (10-12%), coupled with satisfactory calorific value, low sulphur content and fewer alkaline materials in the ash (Efomah and Gbabo, 2015; Yank, Ngadi and Kok, 2016). With these inherent characteristics, an excellent fuel could be produced although the calorific value is lower than wood. Also, there were research works (Wang, Wu and Sun, 2016; Rahaman and Salam, 2017) conducted to utilise rice straw as feedstocks for briquettes production.

A summary has been made by Shafie (2016) from different studies of which the ultimate analysis, high heating value (HHV) and compositions of rice husk and straw from different research are compiled and listed in Table 2.2.

Table 2.2 Ultimate analysis, high heating value and composition of paddy residues

Property	Rice husk	Rice straw
Ultimate analysis		
Carbon (%)	26.69-49.30	38.24-50.10
Hydrogen (%)	2.88-6.10	5.20-5.70
Nitrogen (%)	0.10-0.80	0.87-1.00
Oxygen (%)	27.7-70.05	36.26-43.08
Sulphur (%)	0.08-0.61	0.18
High heating value (MJ/kg)	13.24-15.89	-
Composition		
Lignin (%)	16.27 ± 2.80	9.22±3.01
Cellulose (%)	22.52 ± 0.70	39.74±3.69
Hemicellulose (%)	7.33 ± 0.40	26.03±0.30

Source: Rahmana et al. (2013); Diaz et al. (2015); Shafie (2016)

2.1.2 Sugarcane bagasse

In Malaysia, the sugarcane cultivation is small and not popular as compared to oil palm and paddy plantation. The sugarcane production is focused in the Northwest extremity of Peninsular Malaysia in the states of Perlis and Kedah due to the distinct dry season. For over the past 20 years, sugarcane plantation area has remained at around 20,000 hectares (Salman Zafar, 2015).

Nevertheless, the sugar refiner, MSM Malaysia Holdings Bhd has targeted to establish a refinery worth RM1.1 billion in Tanjung Langsat, Johor. On top of that, MSM's Group Chief Executive Officer Datuk Dr Sheikh Awab Sheikh Abod mentioned that experts in agriculture will be imported to increase the yields of the sugarcane plantation and reconstruct the mills. With this expansion, the annual sugar production capacity of MSM may rise from 1.1 million tonnes to 3.25 million tonnes (Puspadevi, 2015).

With the efforts done by the local company in expanding the sugar industry, it is anticipated that the quantity of residues will increase in accordance to the sugar production. As acknowledged, sugarcane is the main source of sugar and sugarcane juice. From approximately 1 kg of sugarcane, sugarcane bagasse can be generated for as high as 25% of the weight (Kazmi et al., 2016). In Malaysia, the management for the residues are not well-developed and they would be disposed in landfill or burnt in fields. The wastes produced from the sugar industry usually consist of molasses and bagasse and the industry will utilise them for electricity generation, industrial ethanol production, paper manufacturing as well as animal feed.

Sugarcane bagasse is a lignocellulosic by-product and fibrous residue of cane stalks left over after the crushing and extraction of juices (Luz, Gonçalves and Del'Arco, 2007). It is claimed to be one of the good candidates for renewable energy and bio-based chemicals production because of the availability of cellulose, hemicellulose and lignin (Rezende et al., 2011). Mohlala et al. (2016) reported that the satisfactory calorific value of these residues enabled it to be used in the energy production. The property of the sugarcane bagasse is stipulated in Table 2.3.

There is a number of research done to unveil the potential of sugarcane bagasse to be converted into bio-ethanol especially in Brazil, the main global sugarcane producer. Currently, there is limited research done on the production of solid fuel from sugarcane bagasse. However, this natural fibre has been used for the production of commercial products such as lumber material, paper, paper-ware and packaging materials (Asim et al., 2015).

Table 2.3 Property of sugarcane bagasse

Property	Value
Proximate analysis	
Volatile matter	81.50 - 83.66
Fixed carbon	13.15 - 13.30
Ash content	3.20 - 5.20
Ultimate analysis	
Carbon	43.79 - 45.48
Hydrogen	5.96
Nitrogen	1.69
High heating value (MJ/kg)	17.70 - 18.73
Composition	
Lignin (%)	22.2 ± 0.10
Cellulose (%)	35.2 ± 0.90
Hemicellulose (%)	24.5 ± 0.60

Source: Rezende et al. (2011); Yin (2016)

2.1.3 Spent coffee ground

Coffee is recognised as the second largest traded commodity in the word, after petroleum. The main coffee producers are Brazil, Vietnam, Indonesia, Colombia and India. However, Malaysia is least popular in coffee production and ranked at 60th in worldwide, contributing around 0.16% of the world's coffee production (Mohammad Nor and Wahab, 2016). As compared to other agricultural cultivation, the coffee production in Malaysia is relatively small and declining from year to year. The coffee cultivation is only available in few states, namely Sabah, Johor and Kelantan. Table 2.4 presents the data on the planted area and production of coffee in Malaysia from 2007 to 2013.

Table 2.4 Coffee planted area and production in Malaysia

Year	2007	2008	2009	2010	2011	2012	2013
Planted area (Ha)	7,512	3,538	3,426	5,098	5,141	4,277	3,764
Production (tonnes)	21,213	23,061	16,332	15,768	15,064	10,427	14,739

Source: Mohammad Nor and Wahab (2016)

Since the quantity of coffee production in Malaysia is below the demand, coffee beans are mainly imported from Vietnam, Brazil and Indonesia since 2013. Coffee beverages have become a trend among the population especially the youngsters due to the recent development of well-known national and international coffee chains such as

Kopiesatu and Starbucks Coffee stores in Malaysia (Low, Rahman and Jamaluddin, 2015). As a result, the domestic coffee consumption in Malaysia had achieved 650 thousand bags (60 kg each) in June 2013/14, up by 30% from the previous year.

Processing of coffee beans will produce residues such as coffee pulp, cherry husk, silver skin as well as the spent coffee ground. Figure 2.3 depicts the flow of the coffee processing with the percentage of the residues left.

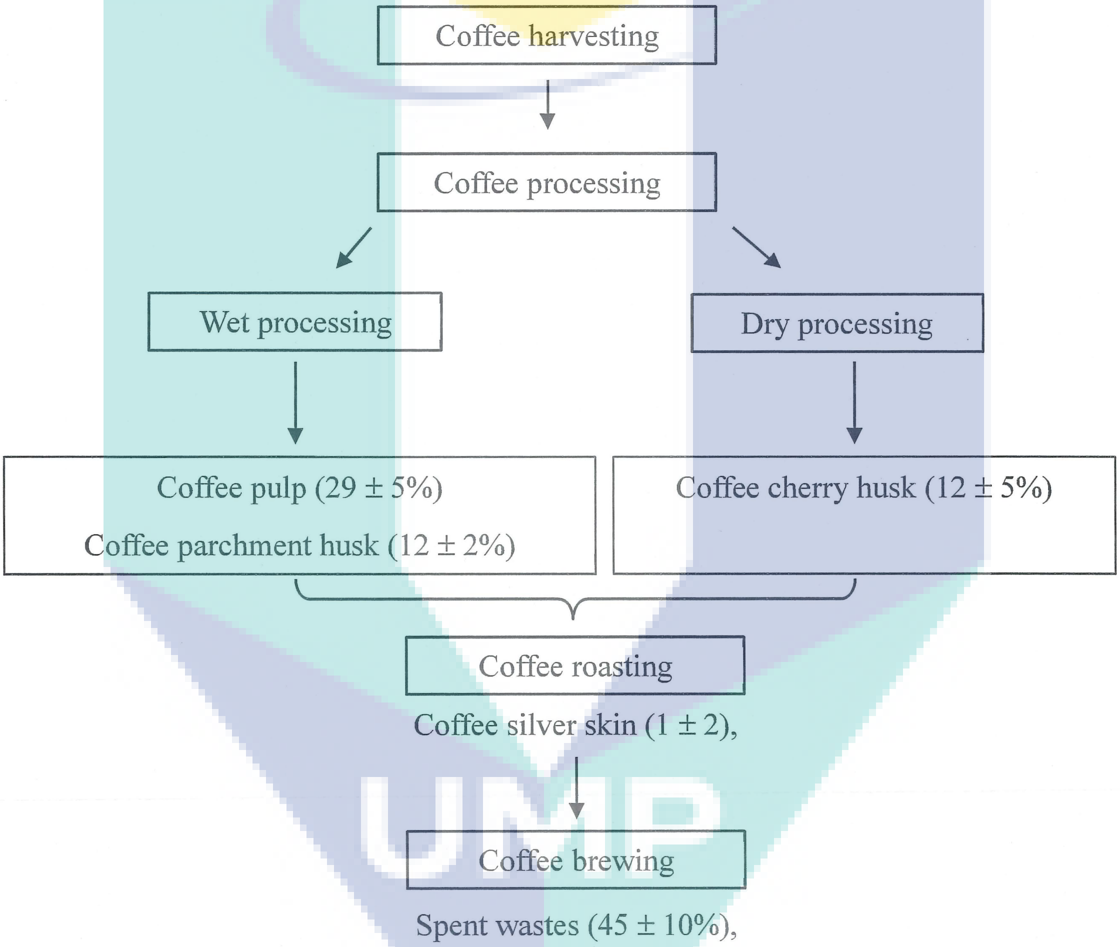


Figure 2.3 The flow of coffee processing
Source: Murthy and Madhava Naidu (2012)

According to the data recorded in Figure 2.3, the spent wastes or coffee ground stands at highest portion (45%) as compared to the rest of the residues. As reported by Murthy and Madhaya Naidu (2015), 65 kg of spent coffee could be generated from about one tonne of green coffee, and approximately 2 kg of wet spent coffee will be obtained from each kg of soluble coffee produced. Due to its outstanding chemical properties as one of the organic matter, it can be used in many applications such as soil fertiliser, heating fuel and so on. Table 2.5 presents the available chemical elements and their respective compositions in the coffee ground.

Table 2.5 Chemical composition of spent coffee ground

Element (%)	Coffee spent
Cellulose	8.6 ± 1.8
Hemicellulose	36.7 ± 5.0
Protein	13.6 ± 3.8
Fat	ND
Total fiber	ND
Total polyphenols	1.5 ± 1.0
Total sugars	8.5 ± 1.2
Pectic substance	0.01 ± 0.005
Lignin	0.05 ± 0.05
Tannins	0.02 ± 0.1
Chlorogenic acid	2.3 ± 1.0
Caffeine	0.02 ± 0.1

Source: Murthy and Madhava Naidu (2012)

A 'Grounds for Your Garden' programme has been promoted by Starbucks coffee company since 1995 (Starbucks Corporation, 2016), contributing a complimentary five-pound bag of soil-enriching spent coffee grounds free of charge through its stores. Basically, the spent coffee can act as fertiliser as well as natural herbicides for gardening purpose, thus disposal to landfill can be avoided. In addition, this particular coffee waste can be used as a renewable fuel resource for heat and energy generation. Nestle, one of the multinational companies in Malaysia has adopted spent coffee ground as a supplemental fuel to replace up to 26.7% of the energy consumption (Low, Rahman and Jamaluddin, 2015). Besides that, initiatives to recycle the spent coffee ground into home heating pellet are currently available because of its suitability as a renewable biomass and energy source.

2.2 Biomass Application

According to Basu (2010), three types of primary fuel in the form of solid (charcoal, torrefied biomass), liquid (ethanol, biodiesel, methanol, vegetable oil and pyrolysis oil) and gaseous (biogas, producer gas, syngas and substitute natural gas) are produced from biomass. These fuels are then further processed through various conversion technologies and used for different purposes for instance cooking, heating, electricity generation, steam generation as well as mechanical or shaft power applications. On top of that, a variety of chemicals are also produced as the by-products (Mande, 2007).

As revealed in the research by Koçar, and Civaş (2013), the energy crops which are sugarcane, sugar beet and maize are widely utilised as feedstocks for bioethanol production. Moreover, various oils are used for biodiesel production in different countries owing to their availability, for example, soybean oil (United States), rapeseed oil (European countries), coconut oil and palm oil (Malaysia & Indonesia). Biogas, on the other hand is collected from the landfill, sewage sludge and other biogas from energy crops such as maize especially in the European Union.

The biofuels for example bioethanol and biodiesel contributed 2.7% of the world's fuels for road transport (Koçar, and Civaş, 2013). Bioethanol usually is mixed with gasoline and biodiesel is blended with diesel in around 5% to reduce the amount of pollutants emitted from motor vehicles. Meanwhile, the landfill gas, sewage sludge gas and biogas are normally used directly for electricity generation.

In Malaysia, there are five different types of biofuels produced from oil palm wastes due to its substantial quantities and continuous supply throughout the year. The biofuels are inclusive of bio-methanol, bio-ethanol, bio-briquettes, pyrolysis oil and lastly hydrogen gas (Mekhilef et al. 2011). Also, a feasibility study conducted by Hosseini and Wahid (2013) discussed about the appropriate strategies to be applied for biogas production from the oil palm wastes.

2.2.1 Types of Biomass Conversion Technologies

Basu (2010) stated that there are two categories of biomass conversion technologies that could be applied to convert the raw biomass into value-added chemicals, fuel, heat and power. Figure 2.4 shows general classification of the biomass conversion routes with processes involved, respectively. The conversion process is normally selected based on the quantity of biomass feedstock, the desired energy carrier, environmental standards and economic conditions. (Saidur, 2011).

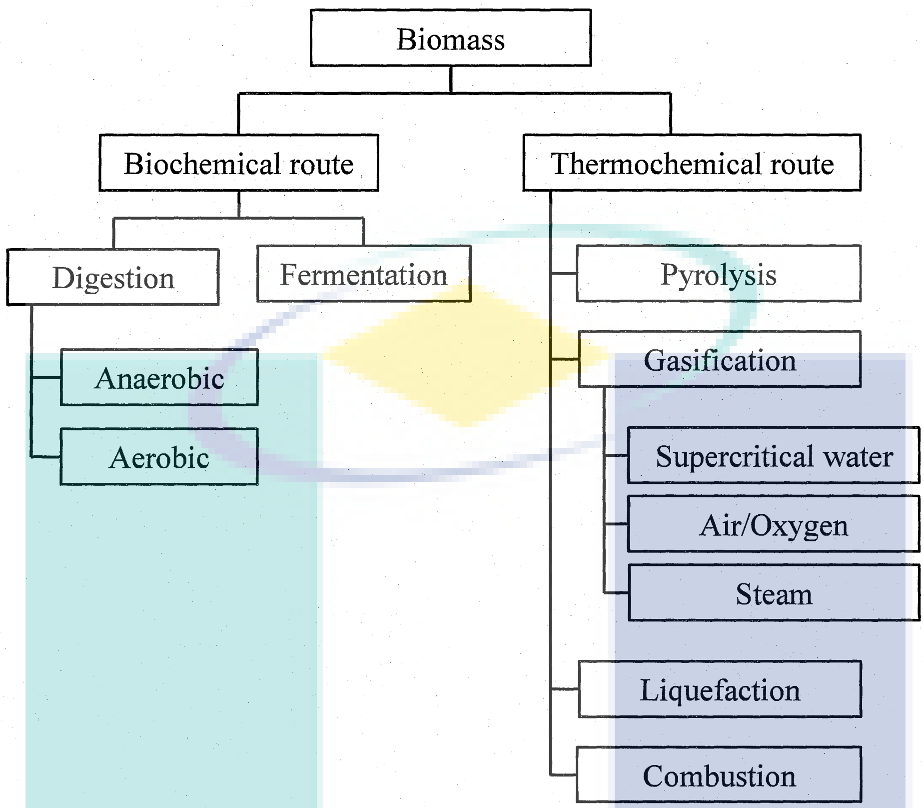


Figure 2.4 Biomass conversion flow

Source: Basu (2010)

2.2.1.1 Biochemical conversion

In the biochemical conversion process, the bacteria or enzymes are used as the medium to break down the biomass into smaller molecules. This process is much slower than thermochemical conversion, but does not require much external energy. According to Saidur and his colleagues (2011), a more comprehensive description on the biochemical conversion process is presented in Figure 2.5. Energy is released from the biomass through the process of anaerobic or aerobic digestion, fermentation and esterification. Biogas, ethanol and bio-diesel are the products which can be used as fuels for transportation as well as for electricity generation. They also mentioned that biomass with higher water content is more suitable to be used in the biochemical conversion process.

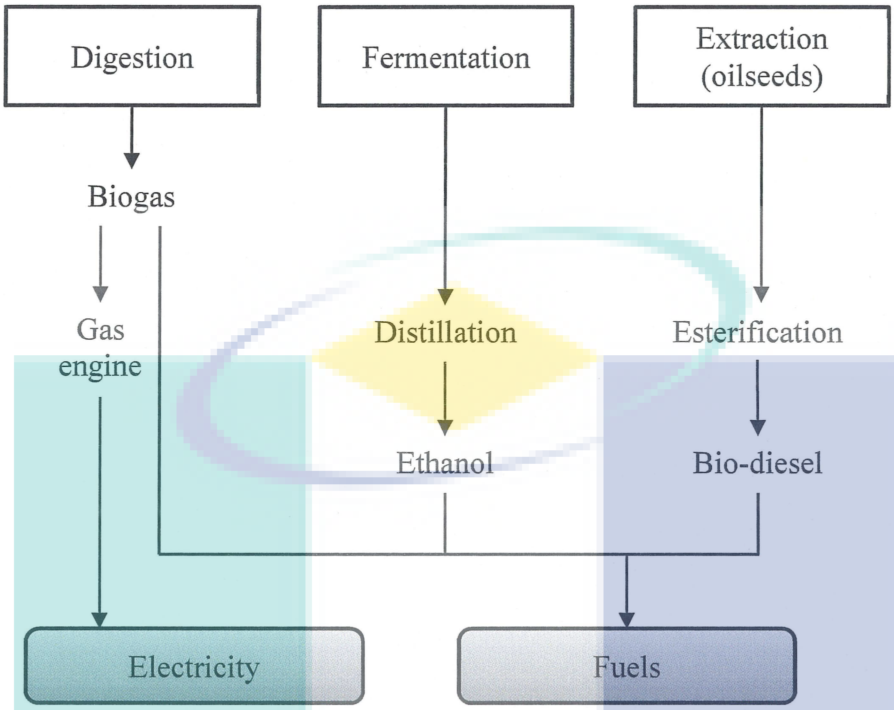


Figure 2.5 Biochemical conversion process for biomass
Source: Saidur et al. (2011)

2.2.1.2 Thermochemical conversion

For the thermochemical conversion, the entire biomass is converted into gases, which can then be synthesised into the desired chemicals or used directly (Basu, 2010). The processes include combustion, gasification and pyrolysis as portrayed in Figure 2.6. Biomass can be directly burnt as fuel for electricity and heat generation, where its combustion system is almost similar to fossil-fuel fired power plants (Saidur et al., 2011). Biomass pyrolysis is another thermochemical conversion method, involving thermal decomposition of the organic matters in the total absence of oxygen. The hydrocarbon rich gas mixture and carbon rich solid residues are the example of end-products from this conversion method, occurring at relatively low temperature. On the contrary, gaseous fuels are obtained from the biomass via gasification in an oxygen-deficient condition with high temperatures (Basu, 2010).

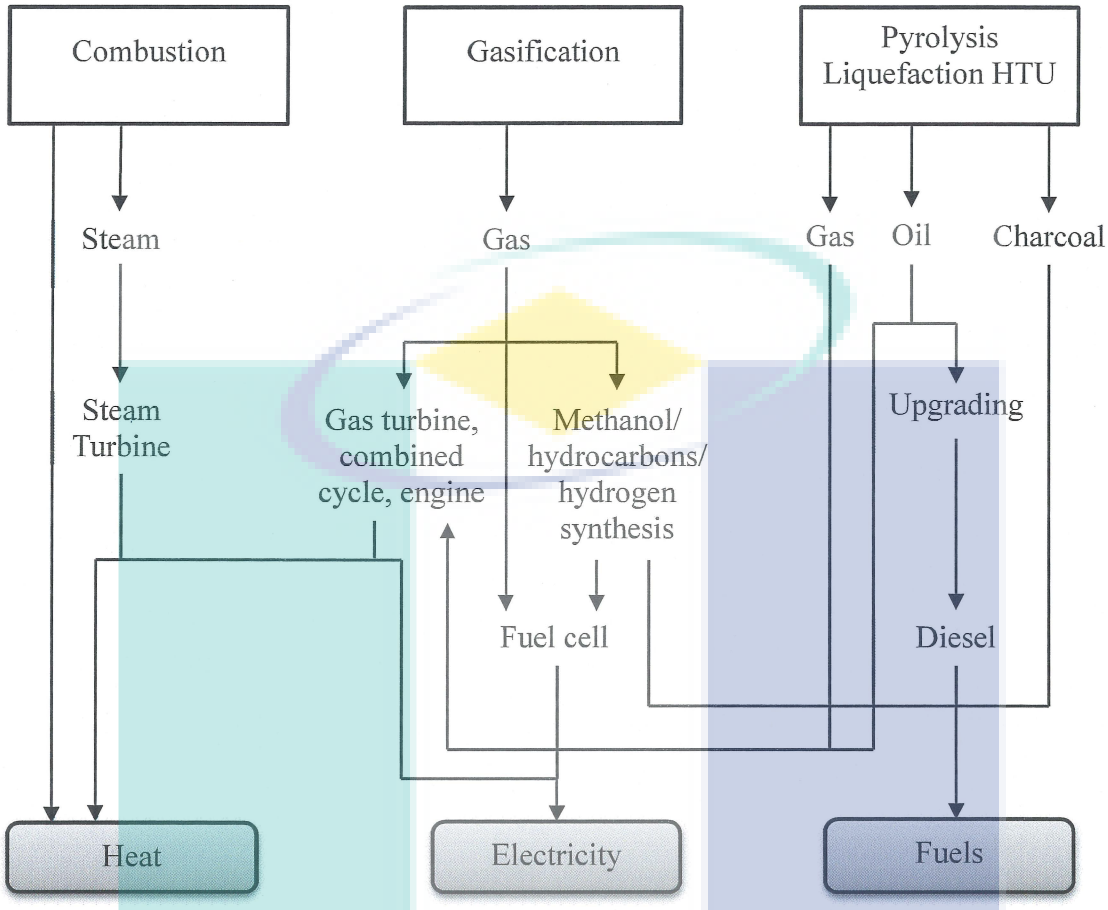


Figure 2.6 Thermochemical conversion process for biomass
Source: Saidur, Abdelaziz, Demirbas, Hossain and Mekhilef (2011)

2.2.2 Energy Constraint

In addition to the conversion of biomass into gas and liquid fuels through various technologies, biomass can also be used as a solid fuel and burnt directed for the heat and power generation (Chen, Peng and Bi, 2015). Current research is focusing on the development of the conversion techniques and processes to boost up the yield as well as to enhance the quality of the liquid and gaseous products (Liu and Han, 2015)

Nevertheless, there are certain limitations on the technologies development for the biofuel generation i.e. cost and energy produced. Liu and Han (2015) reported that further upgrading is required to the bio-oil for it could not be used directly due to its high instability and complex composition. Meanwhile, additional operation cost is needed for the conversion of biomass to liquid fuel and it is also not suitable for certain countries and regions such as rural area (Rezania et al., 2016). Besides that, the large-scale application of the gaseous products in practice is limited due to its low yield as well as its requirement of complicated purification and separation processes (Liu and Han, 2015). Again, the conversion processes, coupled with the technologies employed for the gaseous products are not viable for wide application in all the countries and regions.

On the other hand, biomass combustion alone or co-combustion with coal in existing coal-fired systems for heat and energy generation is claimed to be the lowest risk and least expensive strategy (Liu and Han, 2015). As mentioned by Mwampamba, Owen and Pigaht (2013), direct burning of the residues such as coconut and rice husk, sugarcane bagasse and sawdust in the brick kilns or boilers are commonly practised for electricity generation via steam or gas. However, direct biomass combustion faces great barriers originating from their inherent properties. Thus, a viable option as well as a technology breakthrough is required to improve the biomass utilisation efficiency.

2.2.3 Limitation of Raw Biomass

There are various types of biomass residues available worldwide that could be used as the energy source for heat and electricity generation. Biomass, for instance agricultural residues is normally available in loose, bulky and dispersed form. Therefore, the raw biomass and its utilisation often associate with the challenges of handling, storage, transportation and feeding due to its high moisture content, irregular shape and low bulk density (Kaliyan and Morey, 2009). A very low thermal efficiency and severe air pollution might be resulted from the direct loose biomass combustion for cooking and heating in conventional grates (Pandey and Dhakal, 2013).

Due to its inherent properties, the biomass will not be used alone in power plant, but usually blended with coal for co-firing. However, these challenges could be resolved through the process of densification whereby the use of biomass could be expanded in energy generation. Through the densification process, the raw biomass materials are densified into solid forms and thus could be used for various applications (Oladeji, 2015) listed as follows:

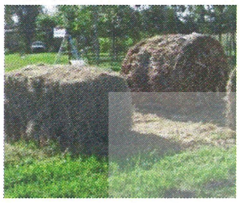
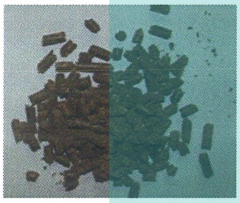
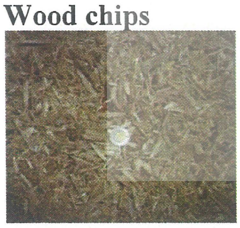
a. Households cooking and water heating
b. Firing ceramics and clay wares (improved cook stoves, pottery and bricks)
c. Fuel for gasifiers to generate electricity
d. Powering boilers to generate steam.
e. Heating productive processes (tobacco curing, fruits, tea drying and poultry rearing)

2.3 Concept of Biomass Densification

According to Chen, Xing and Han (2009), densification is defined as a process of converting low bulk density biomass into high density, energy-concentrated and uniformly shaped biofuel. Pressure is applied with or without heating and binders to overcome the elastic nature of the agricultural wastes and convert them to a compact agromate. This process may enhance the biomass handling characteristics, increase the volumetric calorific value, reduce transportation costs and improve the fuel situation in rural areas (Oledaji, 2015).

The biomass solid fuel could be formed in various shape or structure through the densification process in order to accommodate the usage purpose. As listed in the factsheet by Clarke and Preto (2011), the structure of solid fuel can be in various forms: bales, pellets, briquettes, cubes, pucks and wood chips. Pictures of the example of the solid fuels as well as its respective specifications are briefly presented in Table 2.6.

Table 2.6 The solid fuel types

Solid fuel	Description
Bales 	• Formed using a baler and the shape can be rectangular, square or round. • Large rectangular bales - (0.9 m x 0.9 m x 1.8 m) • Round bales - (1.2 m x 1.5m) to (1.5 m x 1.5 m) • The production of round bales is cheaper, however large square bales are denser and easier to be handled and transported.
Pellets 	• High density, easier to be handled as compared to other densified biomass. • Formed by extrusion process and the standard shape is cylinder. • Dimensions: length (< 38 mm), diameter (~ 7 mm). • Easily break in handling.
Cubes 	• Larger pellets and the shape is usually square • Formed when the chopped biomass is compressed with a heavy press wheel and forced through the dies. • Dimensions: cross section (13-38 mm), length (25-102 mm).
Briquettes 	• Similar to pellets with different size. • Formed by punching the biomass into a die of the piston press under high pressure. • Diameter: (≥ 25 mm)
Pucks 	• Similar in appearance to hockey puck and resilient to moisture. • Formed through a briquetter. • Diameter: (~ 75 mm) • Similar density with pellets, but requiring lower production costs than pellets.
Wood chips 	• Can be applied in household appliances and large-scale power plants. • Formed by using a wood chipper. • Dimension: length (5-50 mm)

Source: Clarke and Preto (2011)

The densified products have homogeneous shape and size which can be easily used in direct-combustion or co-firing with coal, gasification, pyrolysis, and other conversion methods (Kaliyan and Morey, 2009). A variety of approaches and research have been conducted to develop the densification methods and technologies for energy applications. There are physical parameters to be taken into account for biomass densification, which include density, particle size, briquetting pressure, temperature and holding time, bending and compressive strengths, durability, stability and ignitability (Demirbas and Sahin-Demirbas, 2009).

2.4 Densification Technologies Review

Various types of densification systems are developed in order to accommodate the market's demand on the solid fuel production and to improve the handling characteristics of the waste biomass. Different densification processes for instance pelletization, briquetting, extrusion and cubing may require different technology applications. Besides, the technologies adopted in the biomass densification vary with the types of biomass residues or wastes as well as the desired shape of densified product.

There is a wide range of densification technologies or mechanism being implemented and enhanced. As stated in the research of Mwampamba, Owen and Plight (2013), the first patented briquetting technology was available in the mid-1880s in United States. To date, the technologies or mechanism for densification process are being enhanced and commercialised either for household's usage or industrial use for massive production.

2.4.1 Briquette Press

The hydraulic, mechanical and roller presses are commonly applied in briquetting for solid fuel production. The feedstocks with larger particles size and higher moisture contents are allowed to be densified in the briquetting machines without adding any binders. The schematic of a hydraulic or mechanical piston drive is illustrated in Figure 2.7 as mentioned by Tumuluru, Wright, Hess and Kenney (2011).

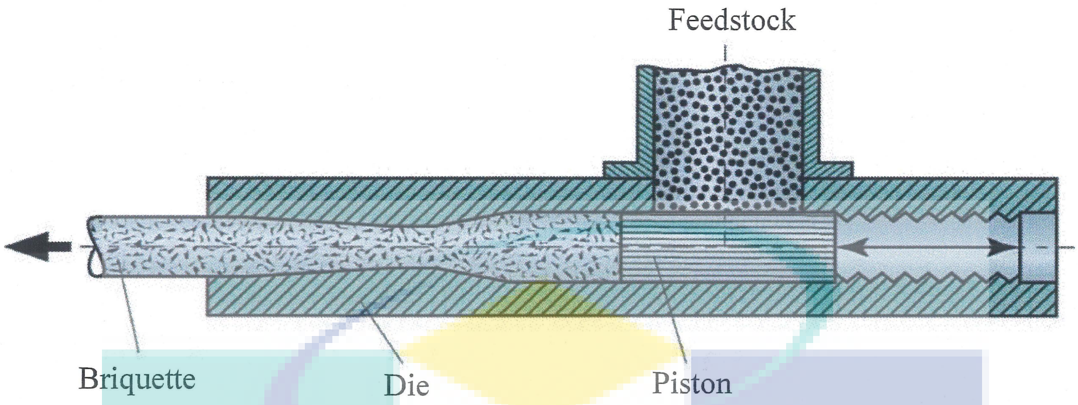


Figure 2.7 Mechanical or hydraulic piston drive
Source: Tumuluru et al. (2011)

In comparison to the mechanical press, the hydraulic piston press is commonly applied in the biomass briquetting process due to its lower output which resulted by the slower movement of cylinder (Tumuluru et al., 2010). A ram and dies concept is applied in this particular in which the biomass feedstock is punched into a die by a reciprocating ram under a very high pressure; hence the mass is being compacted to produce the briquette.

The hydraulic piston presses are available commercially and in a large-scale to accommodate the production capacity and market's demand. As stated by Chen, Xing and Han (2009), a wide range of biomass waste can be compressed by using the piston press for instance corn straw, peanut shell, groundnut shell, cotton stalks and flower stalks.

2.4.2 Screw Press

Researchers (Manickam, Ravindran and Subramanian, 2006; Tumuluru et al., 2011) have presented different versions of screw extruder in their respective studies. Basically, the feedstocks are compacted and extruded via the assistance of a rotating screw which is driven by separate mechanism. High quality briquettes production in addition with the smooth and noiseless operation is the advantages of the screw press (Chen, Xing and Han, 2009).

Tumuluru and his team (2011) reveal that there are four stages required for the screw extruder or screw press as demonstrated in Figure 2.8 to process the biomass namely solids conveyance, initial compression, and final compression and lastly will be discharged. In the first stage, the biomass feedstock is partially compressed and packed where the maximum energy is required to overcome the particle friction. There is formation of local bridges and interlocking particles as the particles are relatively soft and lose their elastic nature due to high temperature in the subsequent stage.

On top of that, biomass also absorbs friction energy in order to be heated and mixed uniformly through its mass. During the last stage of compression, the biomass will enter the heated taper die where moisture is further evaporated to temperatures on the order of 280°C, increasing the compression of the material. During discharge, the uniform log is extruded for the pressure throughout the material normalizes. The unit of biomass heat log produced from this type of screw extruder will have carbonised outer surface and with a hole in the centre to promote better combustion.

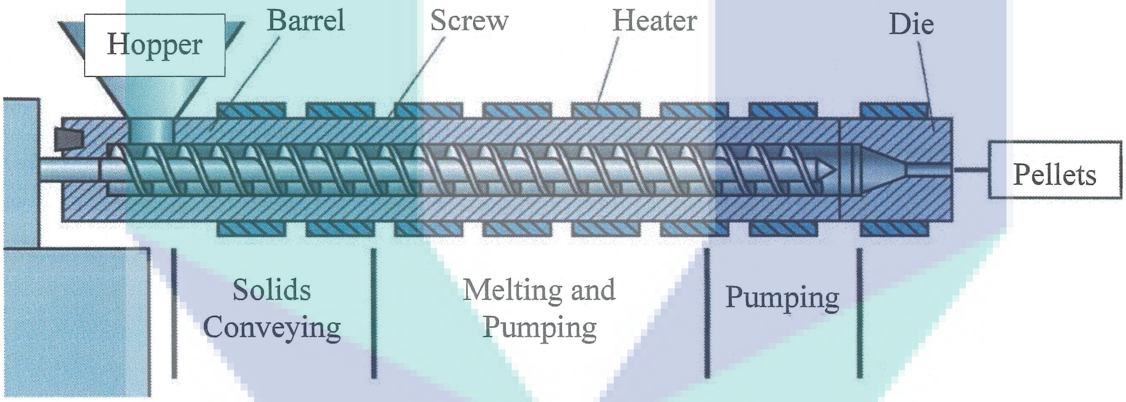


Figure 2.8 Screw extruder
Source: Tumuluru et al. (2011)

2.4.3 Roller Press

The significance of this particular press is the application of two rollers, rotating in opposite direction and compact the feedstocks into pillow-shaped briquettes (Maninder, Kathuria and Grover, 2012). According to Manickam and his team (2009), the roller press in horizontal scale is suitable in producing smaller sized particle of the feedstock in which the flow of the feedstock is controlled by a separate control mechanism after being fed through the hopper. Pre-compression of a small quantity is done by the screw mechanism and lastly the materials are reduced in volume between two counter-rotating rollers. Moreover, Chen, Xing and Han (2009) mentioned that the smaller products formed from the roller press with smaller dies of approximately 30 mm in size are called pellets.

Figure 2.9 shows a roller press introduced in the research by Tumuluru et al. (2011). This particular roller press adopts the vertical compression method, where the feedstocks are compressed vertically of which it is supported by gravitational pull. When two rollers with same diameter rotate horizontally in opposite directions, the biomass is forced through the gap to the small pockets and the agromates are formed subsequently.

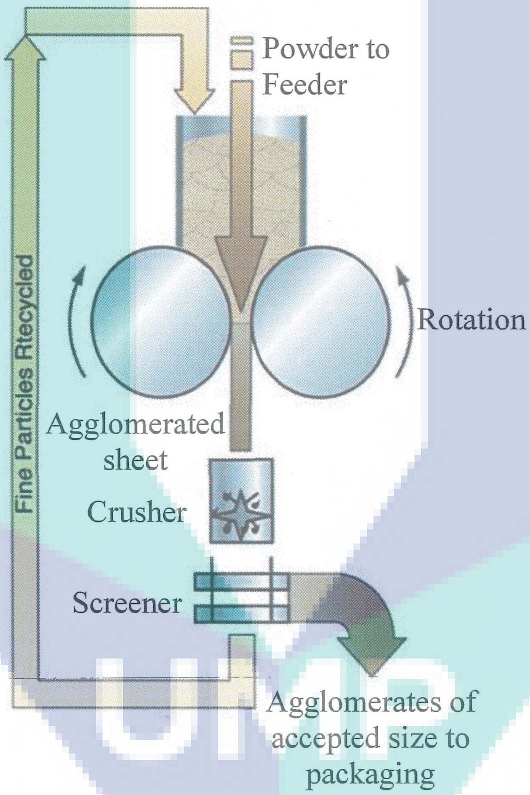


Figure 2.9 Roller press mill
Source: Tumurulu et al. (2011)

2.4.4 Pellet Press

According to Tumuluru et al. (2011), pelletization is the common densification method in feed and fuel manufacturing. It is closely related to briquetting except for the size of the die used; smaller die with around 30 mm in size is required to be used in the pellet press (Maninder, Kathuria and Grover, 2012). As described in the report of

Manickam, Ravindran and Subramanian (2009), the biomass residue is compressed between the roller and annular matrix, where the pellets are expelled out of the perforations. After the discharge, the pellets are cut into length and collected at the bottom of the device. Moreover, pellet press is suggested to be applied in the mass production of pellets for there is no limitation of the device's capacity for the density of the raw material.

As shown in Figure 2.10, there are two rollers in the pellet mills which is a standard commercial unit for higher production rate. There are two different types of pellet presses namely ring die and flat die. For both presses, the rollers will rotate, whereas the die remains stationary during the compression process and vice versa for some pellet mills (Tumurulu et al., 2011).

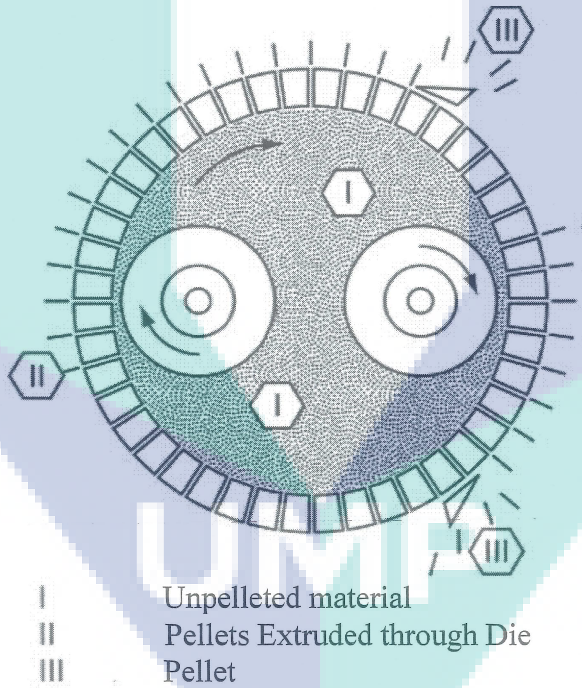


Figure 2.10 Pellet mill die
Source: Tumurulu, Wright, Hess and Kenny (2011)

2.4.5 Cuber

The cuber portrayed in Figure 2.11 shares similar features with the pellet mill with respect to their die ring and press roller. There is an auger to move the chopped feedstocks towards the openings in the die ring uniformly. The exerted pressure for the cuber is normally ranged from 24 to 34 MPa. Therefore, binders are necessary to be added to increase the durability of cubes produced. The cubes are usually cut into 50-75 mm in length by an adjustable deflector which is located outside of the ring.

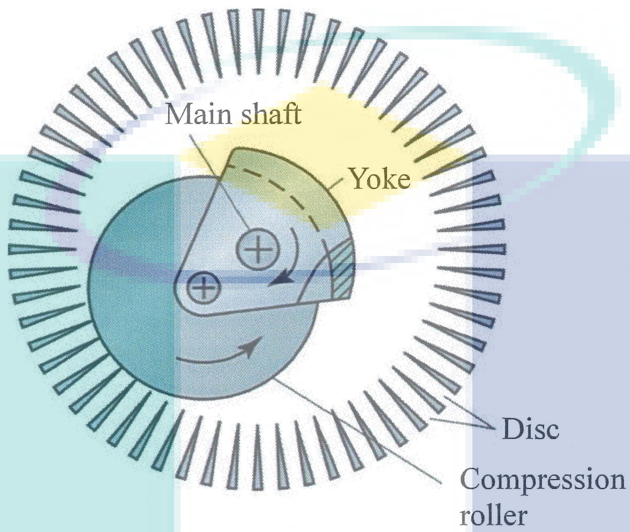


Figure 2.11 Cuber mill
Source: Tumurulu et al. (2011)

2.4.6 Tabletizer

A tabletizer illustrated in Figure 2.12 is equipped with a hydraulic motor and ram which can tightly compact the biomass in a 101.6-152.4 mm diameter cylindrical mold. Through this technology, the feeds are reduced in volume from around 254 to 50.8 mm which is smaller than most of the briquettes. With the application of approximately 137.9 MPa in the mold, the biomass can be glued together without the addition of binders. Long and coarse-cut feedstocks are preferred in the process as they stick together more easily.

However, there are drawbacks of the tableting process of which it is energy-consuming as compared to pelletization. Therefore, the tablets are not tested vastly for various biomass feedstocks as well as the energy density. Besides, assessment on its compatibility to be applied for power plant or as gasification feedstock is also yet to be done. Currently, continuous research is conducted to investigate the energy requirements for producing the tablets using this particular densification technology. In addition, the scale-up process also need to be determined particularly for large-scale production and product application in the areas of co-firing and gasification.

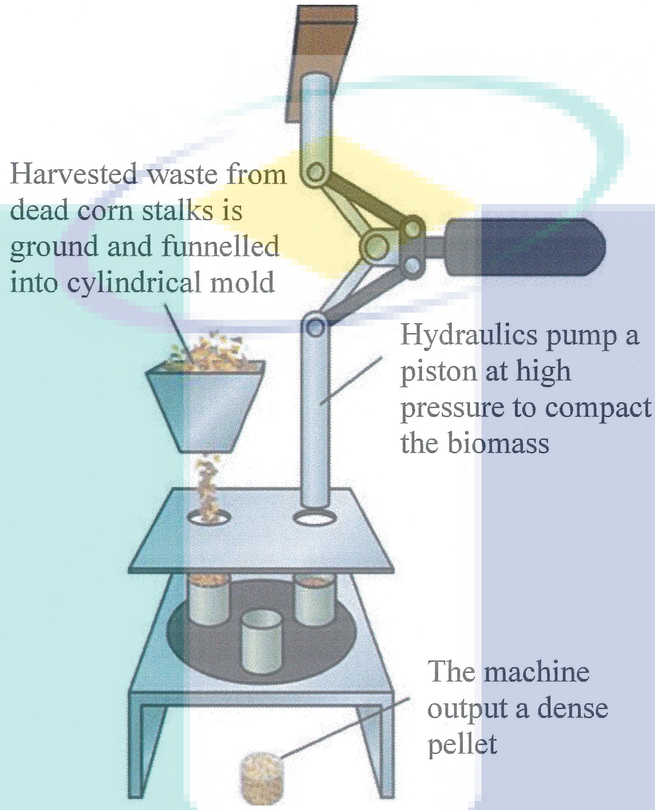


Figure 2.12 Tabletizer
Source: Tumurulu et al. (2011)

2.4.7 Summary

Tumuluru and his team (2011) commented that most of the densification processes will involve both extrusion and compression work. However, it was concluded that more energy is consumed for extrusion work as compared to compression because the material need to overcome the friction during compression and pushing. Table 2.7 lists the specific energy consumption resulted from different densification systems employed to compact different biomass feedstocks. As summarised by Tumuluru et al. (2011), the screw press consumes the most energy among these different systems due to incorporation of compression and other forces such as sharing and mixing. The pellet mill, on the other hand consumes the least energy during densification process.

Table 2.7 Specific energy consumption for different biomass feedstock

Materials	Densification unit type	Specific energy consumption (kWh/t)
Sawdust	Pellet mill	36.8
Municipal solid waste	Pellet mill	16.4
Bark + wood	Pellet mill	30-45
Straws + binders	Pellet mill	37-64
Straws	Pellet mill	22-55
Grass	Pellet mill	33-61
Switchgrass	Pellet mill	74.5
Alfalfa	Pellet mill	30
Straws + binders	Cubing machine	75
Grass	Cubing machine	28-36
Cotton trash	Cubing machine	60
Hay	Cubing machine	37
Sawdust	Piston press	37.4
Straws	Screw press	150-220
Grass	Piston press	77
Straws + binders	Ram extruder	60-95

Source: Tumurulu, Wright, Hess and Kenny (2011)

2.5 Biomass Briquetting Process

Biomass briquetting is one of the promising avenues to convert the loose and ground materials to a homogeneous solid piece with uniform size and high bulk density which can conveniently be used as a fuel. Biomass briquettes produced can fairly be good substitute for coal, lignite, firewood and other non-renewable fuels. It offers a gamut of advantages (Maninder, Kathuria and Grover, 2012; Oladeiji, 2015) as follows:

a. The uniform-sized briquettes are cheap and easy in handling, storage and transportation.
b. Briquettes are renewable and cheaper than coal, lignite and oil.
c. Briquetting process can help to reduce residues disposal problem.
d. It also offers job opportunities for the farmers.
e. Deforestation to obtain fuel wood can be reduced through the utilisation of biomass briquettes.
f. Burning of briquettes can be smokeless, clean and thus does not adversely affect the public's health.

There are different types of biomass briquettes shown in Figure 2.13 with respect to its structure and the processes involved in order to accommodate its application as a fuel.

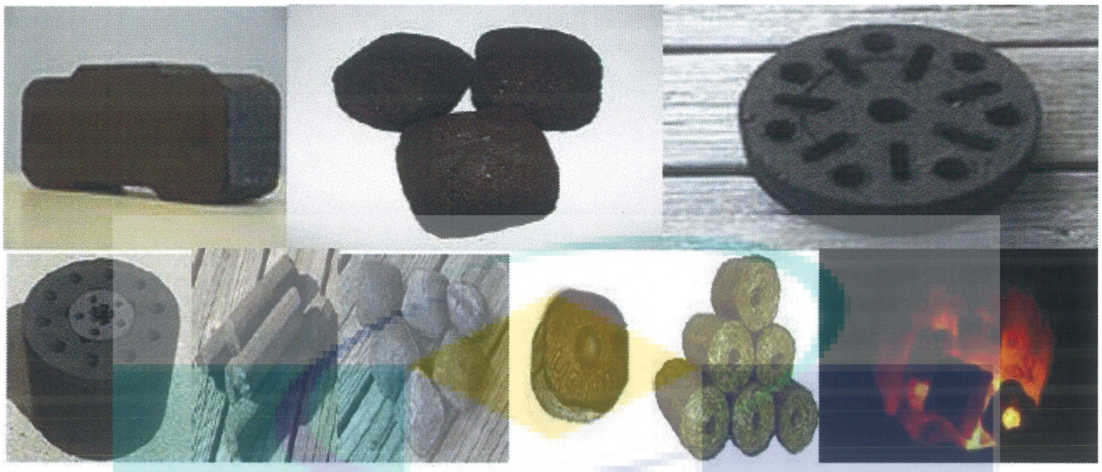


Figure 2.13 Types of briquettes
Source: Sharma, Priyank and Sharma (2015)

Maninder, Kathuria and Grover (2012) mentioned that there are three different methods usually adopted in briquetting process which include direct densification of biomass with binders, pyrolysed/carbonised densification with binder as well as binderless briquetting. According to Mwampamba, Owen and Pigaht (2012), the involvement of carbonisation during this particular densification process can further help to enhance the energy density of the biomass. However, additional energy input was required to carbonise the raw materials before briquetting could be conducted.

On the other hand, the processes involved to generate the briquette are dependent on the types of biomass feedstocks used as well as the desired end-products to be generated. Figure 2.14 presents the relevant steps in briquetting process, applying to different types of biomass residue with different characteristics.

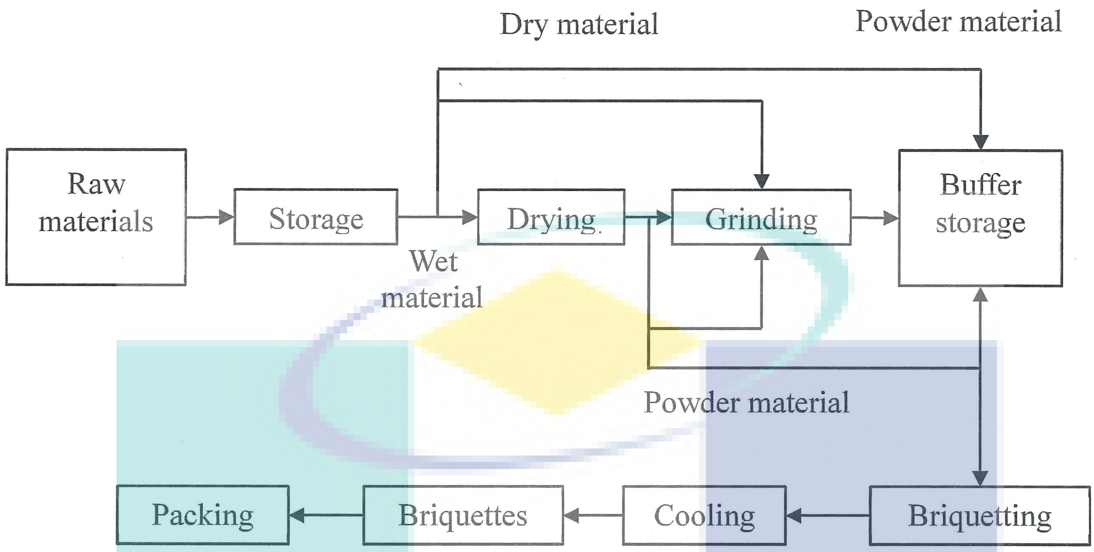


Figure 2.14 Flow of biomass briquette production
Source: Maninder, Kathuria and Grover (2012)

2.5.1 Raw material collection and drying

A wide range of potential waste biomass such as agricultural residues can be used as the feedstocks for the briquetting process. The raw materials will be gathered and stored in a proper space. Cleaning is essential to wash off the contaminants deposited on the waste biomass. Next, the wet materials need to be dried up until a certain satisfactory range of moisture content is achieved. The excessive moisture of the feedstocks can be removed through sun-drying, with a heater or oven and a rotating drum (Cosgrove-Davies, 1985). The drying process can be done before or after size reduction.

As reported in the research of Alade and Betiku (2014), high moisture content will create problems in grinding process and require excessive energy for the process too. Besides, the strength and durability of the densified biomass can be affected if the moisture content within the raw materials is above its optimum level (Clarke and Preto, 2010). Research done by Wongsiriamnuay and Tippayawong (2015) suggested 11-13% of moisture content for the pellets for over a 4-month storage.

2.5.2 Size reduction/ grinding

The dried materials are subsequently reduced in size through the processes such as chopping, crushing, breaking, rolling, hammering, milling, grinding and cutting by the means of grinding equipment (Cosgrove-Davies, 1985). The raw biomass will be ground to a uniform refined size or in powder form through the processes. Besides that, the fines dust must be removed for it will weaken the bonds between particles and cause the solid fuel to break apart during handling.

Through the grinding process, lignin of the material can be partially broken down in order to increase the material's specific area and improve binding. On top of that, more contact points, exposed surface area and surface energy per unit weight are available in the fine powders regardless of theirs physical and chemical characteristics (Tumuluru et al., 2011).

2.5.3 Binding agent

In some briquetting techniques, biomass residues can be compacted without blending the additional binding agent with the feedstock, while in some, binding agents or adhesive materials are added to aid in binding the particles (Sengar et al., 2012). The binders can be categorised as organic or inorganic agents. The examples of the organic binders are heavy crude oil, starch and molasses, while the inorganic binders include clay, sodium silicate and cement (Ugwu, 2013). According to Rahaman and Salam (2017), the addition of inorganic binders will increase burn out temperature and ash content, at the same time reducing heating value of the compacted biomass.

On the other hand, the economic success of the solid fuel formation can be critically affected by the cost of the binders, hence a smallest amount of binder necessary for an acceptable briquette can be utilised. As reported in the article of Cosgrove-Davies (1985), there are two different types of binders namely, combustible and non-combustible binders. Examples of combustible binders are tar, animal manure, sewage mud, fish waste, algae, starch and natural or synthetic resins. Meanwhile, slime, clay, mud and cement represent the non-combustible binders.

Cosgrove-Davies (1985) also mentioned that the use of combustible binder is desirable, but a non-combustible binder can also be employed to produce the good quality briquettes. On the other hand, the additions of binders for the charcoal formation is essential because of the chars are totally devoid of plasticity (Zubairu and Gana, 2014). Teixeira, Pena and Miguel (2010) also emphasize on the usage of binder especially in the carbonised char fines in order to strengthen the charcoal briquettes formed. Meanwhile, Ugwu (2013) verifies that the binder types, amount of binder agent and water addition will pose significant effects on the thermal behaviour and combustion of the briquettes.

2.5.4 Briquetting

During the briquetting process, pressure is applied through the appropriate equipment to the biomass residues to produce a uniform-shaped briquette. The biomass briquetting can be achieved at ambient temperature or elevated temperature, depending on the technology applied. Low densification pressure can be achieved by using the basic hand press. However, hydraulic press or advanced technologies are required to reach a higher pressure for compaction.

Nevertheless, Bazargan, Rough and McKay (2014) mentioned that heating the biomass feedstock during densification is suggested to aid in binding and thus enhance the durability of the densified product. Lignin in the plant residues softens at elevated temperature, at certain level and acts as the natural binder to enhance the particles binding during the briquetting process (Adapa, Tabil. and Schoenau, 2009).

On top of that, there are differences between the mechanisms of the technologies described and thus need to be well chosen, strongly built to process the briquettes. Besides that, the variables such as briquetting pressure and dwell time, feedstock oxidation and moisture, the weight of material briquetted, temperature and humidity during cure, sample mixing, and briquette crushing speed need to be well-controlled in order to produce the briquettes with better quality (Mwampamba, Owen and Pigaht, 2013).

2.5.5 Cooling and packaging

The process of cooling and packing is the last stages to handle the produced densified products. The end products normally will be hot and plastics once extracted from the press due to the frictional force developed within the system (Kaliyan and Morey, 2009). Therefore, certain briquettes are required to be passed through a drying oven with proper temperature adjustment to cure or placed under the sunlight for a period of time. A typical example is presented in the report of Morrison, Banzaert and Upton (2013); the Papyrus briquette produced are placed in the drying oven overnight with the temperature of 70°C or until constant weight is obtained.

After the cooling process, the densified products would be packaged and stored at room temperature. As described in the research of Wongsiriamnuay and Tippayawong (2015), the produced pellets were kept in an airtight bag and stored at room temperature to avoid the effect of moisture from air to the pellets formed. They also mention that there is availability of the bonding sites for the water molecule to bond with the OH-bonding group from the hemicellulose and cellulose structures.

2.6 Binding Mechanism

Besides the pressure compaction, there are also other fundamental aspects for briquetting process including binding mechanism and compaction mechanism (Alade and Betiku, 2014). The strength and durability of densified biomass are dependent on the particles bonds, which are affected by some of the process variables, for instance die diameter, die temperature, pressure, binders, and preheating of the biomass mix (Tumuluru, Wright, Hess and Kenny, 2011). During the biomass densification process, the possible binding mechanism acting between the particles can be sub-divided into five main categories: solid bridges, attraction forces between solid particles, mechanical interlocking bonds, adhesion and cohesion forces and interfacial forces and capillary pressure (Manickam, Ranvindran and Subramanian, 2006; Maninder, Kathuria and Grover, 2012).

Based on the review article of Tumuluru and his team (2011) as well as Oladeji (2015), further explanation and details on the types of binding forces can be summarised in Table 2.8.

Table 2.8 Types of binding mechanism during densification

Binding force	Description
Solid bridges	Developed through chemical reactions and sintering solidification, hardening of the binder and melted substances, or crystallisation of the dissolved materials.
Attraction force between particles	Creates van der Waals force, prominent at extremely short distance between adhesion partners Contribute significantly to the particles adherence.
Mechanical interlocking bonds	Occurs during the agitation and compaction of fibrous, flat-shaped and bulky particles.
Adhesion and cohesion forces	Happened at the solid-fluid interface and within the solid, very similar to solid bridges.
Interfacial forces and capillary pressure	Developed with the presence of liquids, like water, during densification.

Source: Tumuluru et al. (2011); Oladeji (2015)

As reported by Tumuluru et al. (2011), the compaction of ground biomass residues involved three different stages with regards the binding mechanism. Firstly, the biomass particles are rearranged in a closely packed form at a low pressure and its original properties are retained. At the same time, the inter-particle and particle-to-wall friction trigger energy dissipation. During the second stage, the particles are forced against each other where plastic and elastic deformation occurs. Due to the significant increment of the inter-particle surface contact, particles are bonded through the van der Waals and electrostatic forces.

In the last stage, the deformed and broken particles are fixed into position due to a decreased number of cavities with a 70% inter-particle conformity. It is also crucial to understand that the yield point of the material governs the rate of approach to the true density of the product. Because the loading is hydrostatic in character, the applied force will fracture the brittle particles and possibly result in mechanical interlocking. Figure 2.23 portrays the flow of powder particles deformation under compaction.

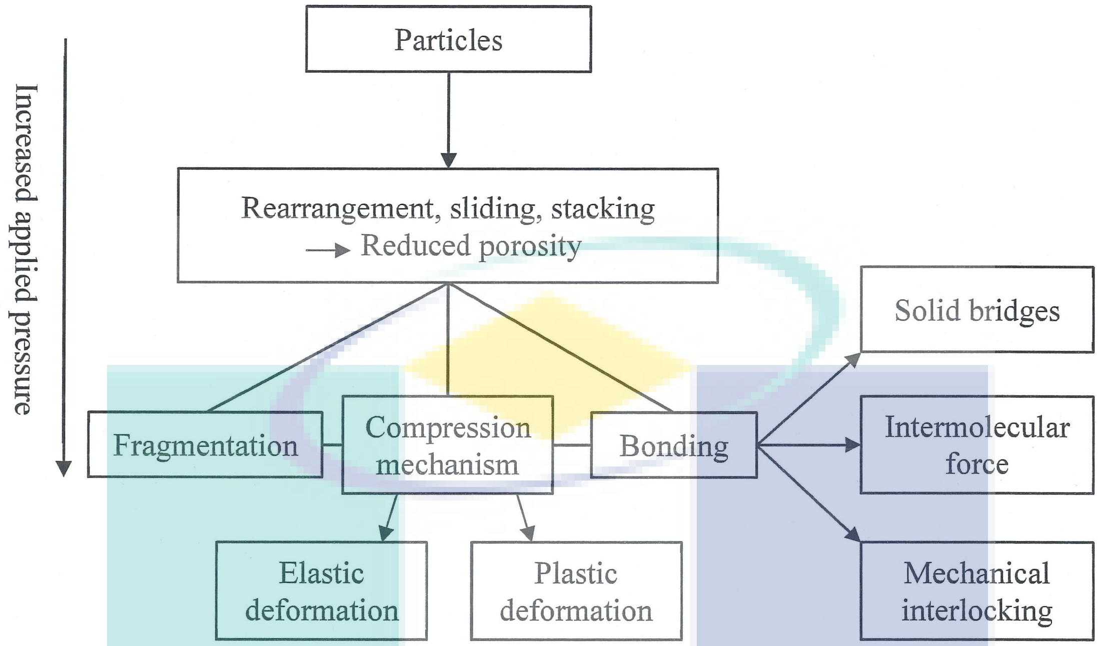


Figure 2.15 Deformation mechanisms of powder particles under compaction
Source: Tumuluru et al. (2011)

The binding mechanism of binderless briquetting technology was further discussed by Oladeji (2015). The lignin available in lignocellulosic biomass is a non-crystallised aromatic polymer and its melting point is not fixed. However, lignin will start to soften, melt and liquefy when the temperature reaches 200-300°C. The residues lose their elasticity and are easily compressed. With the high pressure applied, the melted lignin will glue the cellulose together and solidify to form a briquette. Oladeji reveals that mechanical locking and particles' adhesion can be created and increased respectively from the biomass densification with high pressure, forming intermolecular bonds in the contact area.

Rahaman and Salam (2017) commented about the binding mechanism of rice straw which was compacted using cold densification method. They mentioned that solid bridges could not be formed due to the absence of heat. At compression stage, rice straw particles are rearranged and subsequently experience elastic deformation (reversible), plastic deformation (irreversible) which form the interlocking bonds, and generate short-ranges forces (molecular, electrostatic and magnetic). In the presence of moisture, interfacial forces and capillary pressures will develop when pressure continue to rise, and thus increase the cohesion between rice straw particles and form liquid bridges.

2.7 Measurement of strength and durability of densified biomass

The quality of densified products will be an indication for the success of briquetting process. The biomass briquettes/ pellets must meet the market standard as well as consumer's requirements whereby one of the concerns will be on dealing with their strength and durability.

As summarised by Kaliyan and Morey (2009) in their review article, four different experimental tests could be conducted to measure the effectiveness of the inter-bonds formed during the briquetting process in terms of strength and durability. The analyses covered compressive resistance, water resistance, impact resistance and lastly abrasive resistance test. A detailed explanation on the definition, methods and related equipment are summarised in Table 2.9 and Table 2.10.

Table 2.9 Mechanical strength and durability analysis – Part A

Analysis	Definition	Method
Compressive resistance/ strength	• The maximum crushing load that a densified product can withstand until cracking or breaking. • Simulate the compressive stress caused by weight of the top pellets on the lower pellets during storage in bins or silos, crushing of pellets in a screw conveyor and chewing of feed pellet between animal teeth. • A quick measure on quality of the pellets to help in adjusting the pelleting process and enhancing the quality of densified product.	❖ Diametrical compression test, the specimen is placed between two flat and parallel plates. The load is then increased gradually at a constant rate until the sample breaks or cracks ❖ ASTM standard method: C39-96 for the concrete briquettes ❖ Equipment: Kahl tester, Strokes tester, Schleuniger tester, tablet hardness tester, Instron universal testing machine and Kramer shear strength tester
Water resistance	• The physical quality of the densified products can be affected by short-term exposure to rain or high humid conditions during transportation and storage.	❖ The immersion test is used to measure the water gained by a briquette after immersing in water.

Source: Kaliyan and Morey (2009)

Table 2.10 Mechanical strength and durability analysis – Part B

Analysis	Definition	Method
Impact /drop/ shattering resistance	• Simulate the forced encountered during emptying of densified products from trucks on ground, or from chutes into bins. • The safe height of pellet production could be figured out too from this drop test.	❖ The specimen is dropped from a determined height. The impact resistance in percent is then identified after the definite drops. ❖ Formula: $\lvert R\rvert = (100x\ N)/n$ where N= number of drops; $n =$ total number of pieces after N drops. ❖ ASTM method: D440-86 of drop shatter test for coal to estimate the impact resistance of biomass logs
Abrasive resistance	• The mechanical handling of the samples could be simulated via the test and thus predicting the possible fines produced during tumbling due to impact and shearing between pellets and over the wall of the can.	❖ The pellet durability index or percent durability ❖ The common equipment is tumbling/ durability can, Holmen tester and Ligno tester

Source: Kaliyan and Morey (2009)

Besides methods reviewed by Kaliyan and Morey (2009) in Table 2.9 and Table 2.10, there were recent research conducted for the similar analyses by using different experimental approaches to investigate the strength and durability of the densified products. Table 2.11 and Table 2.12 list some of the relevant research done to determine the mechanical properties of the briquettes formed.

Table 2.11 Relevant research on mechanical properties analysis for densified product – Part A

Analysis	Author	Method
Compressive resistance	Yuhazri et al. (2012)	The compressive strength of the 68 g fuel briquette (40 mm in diameter and 73 mm in length) is measured using Universal testing machine in lateral position at the speed rate of 1.3 mm/min
	Mitchual, Frimpong-Mensah and Darkwa (2013)	The compressive strength in cleft of briquettes (approximately 90 g) is determined using Instron universal strength testing machine with 100 kN of load cell and cross-head speed of 0.305 mm/min.
	Bazargan, Rough, McKay (2014)	The sample was located on its side on a stainless steel base platen, the top platen with 40 mm diameter was lowered with a speed rate of 0.5 mm/s until the sample cracks.

Table 2.12 Relevant research on mechanical properties analysis for densified product – Part B

Analysis	Author	Method
Water resistance	Sengar et al. (2012)	The briquette is immersed in a container filled with 25 mm of water at 27°C for 30 seconds.
	Davies and Davies (2013)	Percentage of water resistance capacity of dry briquette was investigated when immersed in cylindrical glass container containing distilled water at 29 ± 2°C for 120 seconds.
	Bazargan, Rough, McKay (2014)	The water resistance was obtained by subtracting the percentage of water absorbed by the densified product from 100% after it was immersed in water at room temperature for 1800 s (30 min).
Impact resistance	Sengar et al. (2012); Birwatkar, Khandetol, Mohod and Dhande (2014)	The briquette with known weight and length was dropped on RCC floor and concrete floor from 1 m height for 10 times.
	Bazargan, Rough, McKay (2014)	The densified products were dropped from 1.85 m onto a metal surface 4 times and the weight retained is recorded. Each briquette was repeatedly dropped from the 2 m height onto a concrete surface until it fractured and the impact resistance index, $\|R\|$ was used to calculate the shatter resistance.
	Saikia and Baruah (2013)	ASTM D440-86 method is used to figure out the impact resistance index. In the drop test, briquettes are dropped twice from a height 1.83 m onto a concrete floor.
Abrasive resistance	Sengar et al. (2012)	The briquettes were placed in a 30x30x45 cm cuboid made of angle iron frame that fixed over a hollow shaft. The cuboid with briquettes inside were then rotated for 15 minutes.
	Repsa, Kronbergs, Pudans (2014)	EN 15210-2:2011 is the standard used to measure the durability of briquettes. A minimum (21±0.1) kg of briquettes were placed in a durability drum and rotated at (21±0.1) rpm for 5 mins or for (105±0.5) rotations.
	Lunguleasa (2012)	3 wooden briquettes were subjected to vibration inside the specifically designed vibration box for 5 minutes, above of sieve of 3 mm.

According to Kaliyan and Morey (2009), there are no standardised criteria on the acceptance levels for compressive resistance, impact resistance, water resistance and abrasive resistance of the biomass densified products in the United States. Different researchers did come out with their respective acceptance limit for the strength and durability of the densfiied products.

Nevertheless, Kaliyan and Morey (2009) also revealed that researchers come out with different classification for the straw cubes; when the durability of the cubes is between 80-90%, they are considered good, whereas a 'very good' rating was given to the straw cubes with the durability of 90% and above. The acceptance level for compressive strength of coal briquettes was suggested to be 375 kPa; impact resistance index at 50 and 95% would be the acceptance level for water resistance as well as the durability. On top of that, Borowski (2009) also mentioned that the gravitational resistance to drop for the briquettes should achieve a value higher than 90%.

2.8 Factors affecting the strength and durability of densified products

According to Kaliyan (2008), process variables need to be taken into consideration in order to produce solid fuel with desired strength, durability and quality. The examples of variable include moisture content, particle size, preheating temperature and compacting pressure. The strength, durability and density of the briquettes formed could be influenced significantly by the briquetting pressure, temperature, moisture content as well as particle size. On top of that, Križan, Šooš and Vukelić (2009) mentioned that if the pressing temperature, pressure and material humidity are not in optimal interval, the pressed product are not compact and might break into pieces easily.

2.8.1 Moisture Content

Water or moisture of the biomass plays a crucial role in densification as a binding agent as well as a lubricant (Kaliyan and Morey, 2009). It may help in heat transfer as well as enhancing the plasticity of the material. If the moisture content of the material is too low or too high, the strength and durability of the densified products will be affected (Kaliyan and Morey, 2009). In the same review article, several examples of the past research are listed. The maximum quality of the briquette from water hyacinth could be achieved with the moisture range of 8 to 12% (w.b.). Too dry or too wet of water hyacinth could not be densified, causing the re-expansion of the briquettes.

Another example mentioned by Kaliyan and Morey (2009), a study was done on corn stover briquetting by increasing its moisture content from 10 to 15% (w.b.), the result showed that there is an increment on the briquette's durability from 62 to 84%. Moreover, the stability or integrity of the pellet was the best between the moisture levels of 5-15%. However, the pellets are not stable at the moisture content above 20% (Stelte et al., 2011).

A brief explanation from Križan, Šooš and Vukelić (2009) stated that the excess water in the material due to high humidity will turn into steam during densification process, tearing the briquette into pieces. On the contrary, very high pressure is required for a quality briquette production when the moisture content is below than 10% and it is costly. A different point of view was obtained from Pandey and Dhakal (2013) which stated that 8-12% is the acceptable range of moisture content for briquetting or in most cases; it can be up to 15% as the moisture limit. Other researcher added that some materials with the moisture content up to 20% could be briquetted in a piston press.

A research was conducted by Jiang et al. (2014) to investigate the effect of moisture content of the materials to the relaxed density and Meyer hardness of the densified products. As shown in Figure 2.16, the results showed that the appropriate moisture content used to produce the pellets with highest relaxed density and Meyer hardness values ranged from 10-15%. However, the moisture content above or below this range would negatively affect the quality of pellets.

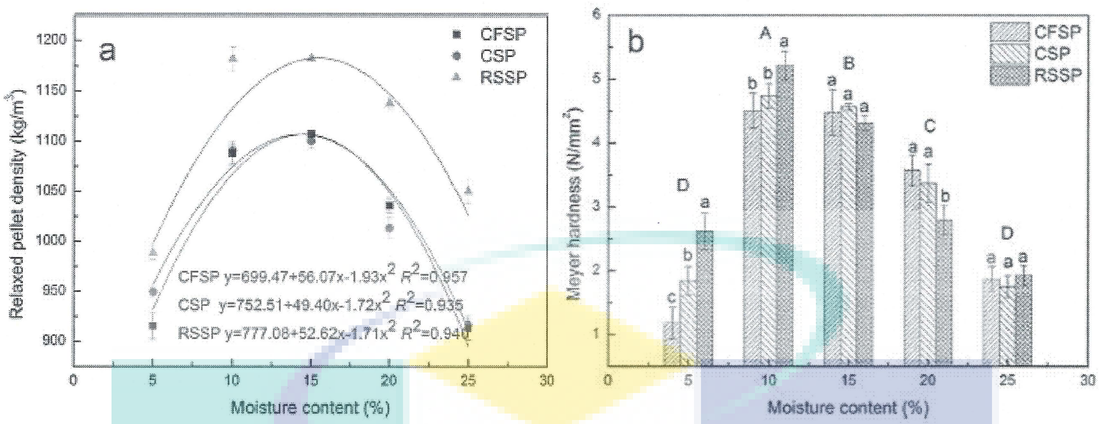


Figure 2.16 Effect of moisture content on (a) relaxed pellet density and (b) Meyer hardness of the pellets
Source: Jiang et al. (2014)

2.8.2 Particle Size

Although particle size might not have significant effects onto the products as compared to other parameters such as temperature and pressure, it might still contribute to increased unit density as well as durability of the resulting products. The finer the particles size, the easier the briquetting process would be. Fine particles will provide larger surface area and beneficial to particles bonding when pressure is applied. Size reduction can be done by means of hammer mill, some materials for example wood or straw might need be chopped before hammer milled (Maninder, Kathuria and Grover, 2012).

An agreement was obtained from (Bazargan, Rough and Mckay, 2014) of which finer particles are known to have greater contact surface area per unit volume and higher number of contact points, contributing to the higher strength of the densified products. He also emphasised that too small of the particles size will cause cloggage problem within the facility. Hence, a mixture of various sized particles is suggested to be adopted and the particles can vary in size from batch to batch, resulting with nearly no inter-particle spaces within the densified fuel.

On the other hand, more power/energy is required for briquetting if the particles size is larger. The increased particles size might weaken the binding forces of the briquette formed, resulting in a quick decay when it is burnt (Križan, Šooš and Vukelić, 2009). In a nut shell, determination on the particle size for briquetting is crucial as it might affect the strength, durability as well as the burning rate of the densified products significantly.

2.8.3 Preheating Temperature

The preheating temperature exhibits an expressive impact on the quality and strength of the briquettes formed. In addition, preheating biomass could significantly increase the throughput of the pelletizing machine as well as reduce the energy requirement per kilogram of pellets formed. According to Adapa, Tabil and Schoenau (2009), biomass is made up of the chemical components namely cellulose, hemicelluloses, protein, starch, lignin, crude fibre, fat, and ash. These components will be activated and act as natural binding components when the biomass feedstock is heated to the temperature ranging from 75-150°C (Wongsiriamnuay and Tippayawong, 2015). On top of that, within the range of 100 to 200°C, higher durability pellet can be obtained as a result from the cross-linking of protein, starch and lipid.

Lignin is released only at specific elevated temperature and actually it has a low melting point of about 140°C (Chen, Xing and Han, 2009). Its softening temperature varies with types of biomass residues and the lignin isolation method. Lignin will soften, melt and exhibit thermosetting properties, enabling the biomass to be compressed easily. The presence of those binding elements could contribute in the binding process as it denatures and plasticises during the densification and positively influence the hardness and durability of the briquette (Tumuluru, Wright, Hess and Kenny, 2011). Protein will re-associate and bonds can be established between different particles (Chen, Xing and Han, 2009).

A high quality briquette could not be achieved if the preheating temperature is lower that the optimal value. Mitchual et al. (2013) found that the solid bridges formation from the chemical elements of the biomass might be absent or minimal when the solid fuel is produced at room temperature. Higher temperatures used for the densification process will result in greater durability of the final products as compared to room temperature (Wongsiriamnuay and Tippayawong, 2015). As reported by Kaliyan and Morey (2009), preheating temperature is limited to 300°C to avoid decomposition of biomass materials as well as damage to the pellet mill and particular consumables.

From Kers et al. (2010), the briquette strength increases with the increasing temperature when compacting pressure is at constant value, but only to a specific value. As shown in Figure 2.17, the optimal pressing temperature of the curve is where the maximum briquette strength properties are achieved. Increasing the pressing temperature may lead to the occurrence of highly volatile elements or the feedstocks to burn. On the other hand, the briquette will become unstable and lower in strength when the temperature used is below than the optimal value, and thus causing it to burn for a shorter time.

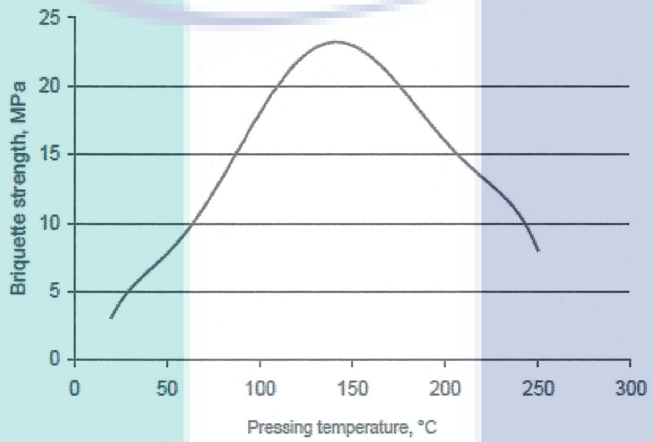


Figure 2.17 Dependence of the briquette strength on the pressing temperature
Source: Kers et al. (2010)

The study done by Jiang et al. (2014) is consistent with that of Kers at al.(2010) whereby the relaxed densities and Meyer hardness of the pellets as demonstrated in Figure 2.18 increased when the die temperature increased from 30-110°C, but decreased with further die temperature increasing. Therefore, the optimal preheating temperature used to produce the quality pellets from the mixture of Chinese Fir and Sewage Sludge (CFSP), Camphor and Sewage Sludge (CSP) and Rice Straw and Sewage Sludge (RSSP) should be around 110°C.

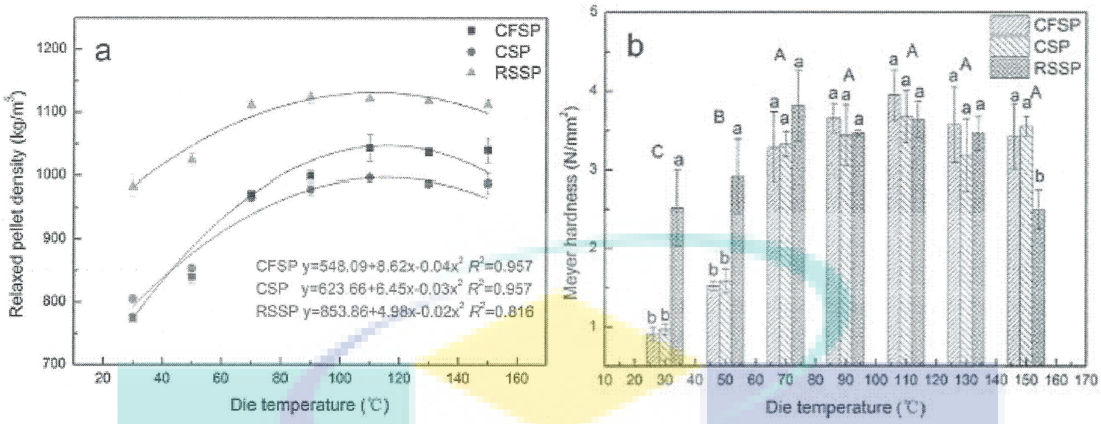


Figure 2.18 Effect of die temperature on (a) relaxed pellet density and (b) Meyer hardness of the pellets

Source: Jiang et al. (2014)

2.8.4 Compacting Pressure

Looking from the aspect of pressure, Adapa, Tabil and Schoenau (2009) revealed that high compression pressure is applied during the densification process to damage the cell structure of the biomass particles whereby protein and pectin are released consequently. These compounds can be the natural binders to help in particles adhesion. A similar review was supported by Sengar and his team (2012), higher pressure is required for the briquetting of agricultural wastes in order to overcome the material's springiness and its cell wall will be destructed with the combination of heat and pressure.

As listed in the published article of energypedia (2015), there are different compacting pressure applied in the densification pressure, depending on the types of feedstocks and technologies used. Three different pressure levels are categorised as follows:

- Low pressure: up to 5 MPa
- Medium pressure: 5 to 100 MPa
- High pressure: above 100 MPa

This article also stated that the low pressure densification is suggested to be done with the addition of binders, while binder addition is optional for medium pressure densification. However, the inherent binder (lignin) will be released under high pressures, thus additional binders are not necessary.

Briquette strength increases with the increase of compacting pressure (Kers et al., 2010). Muazu and Stegemann (2015) pointed out briquettes compacted at lower pressure from 30 to 60 MPa will crumble easily, whereas those manufactured at higher pressures of 150-250MPa remain compacted and durable. In the review article of Kaliyan (2009), there is relevant research proving that the increased in the durability of the corn stover briquettes from 50-62% when the compacting pressure was adjusted to 150 MPa from the initial 100 MPa.

In addition, the similar outcome is obtained by Wongsiriamnuay and Tippayawong (2015) as portrayed in Figure 2.19 in which the durability of the densified cob and stalk increased from 35% to 50-60% and from 28 to 40% for husk with the increasing pressure from 150 MPa to 250 MPa. On top of that, research of Rajaseenivasan and his team (2016) also observed that increasing the compacting pressure from 7 to 33 MPa has resulted in a gradual increment in the shatter index, durability index, impact resistance and water resistance of the briquettes produced from saw dust and neem powder as shown in Figure 2.20.

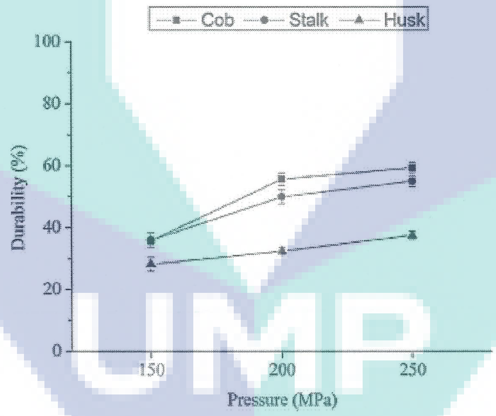


Figure 2.19 Durability of maize pellets at 30°C
Source: Wongsiriamnuay and Tippayawong (2015)

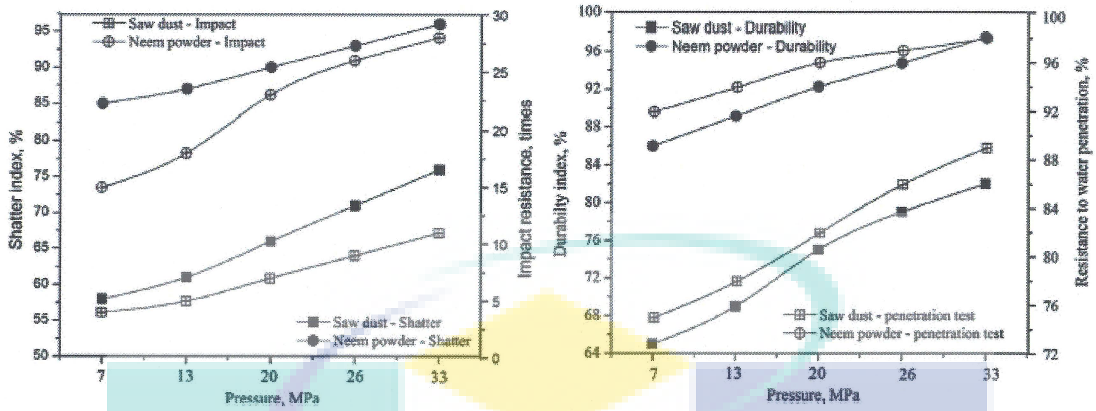


Figure 2.20 Shatter index, impact resistance, durability index and water resistance of the briquettes with blend of sawdust and neem
Source: Rajaseenivasan, Srinivasan, Qadir & Srithar (2016)

On the other hand, preheating of biomass before densification might reduce the required compacting pressure in the briquetting process and at the same time, a better density and high quality of end-product could be obtained. Križan, Šooš and Vukelic (2009) found that there is a relationship of the compacting pressure and pressing temperature for the compaction of pine sawdust whereby increasing the pressing temperature during densification requires lower pressure and vice versa as illustrated in Figure 2.21 below.

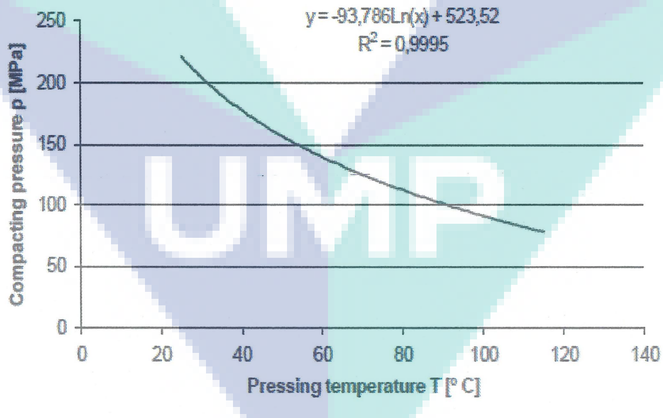


Figure 2.21 Dependence of the compacting pressure on the pressing temperature
Source: Križan, Šooš & Vukelic (2009)

2.8.5 Mixing of biomass materials

Kaliyan and Morey (2009) reveals that there are several studies done on the mixing of a feed ingredient or biomass material with high natural binding capacity together with the base feed in order to enhance the strength and durability of the densified products. A similar agreement is reported by Altawell (2014), fuel mixing from different types of biomass materials was meant to increase the fuel quality, standard fuel characteristics and reduce costs as well. On top of that, different blends ratio either in terms of weight or percentage could also affect the quality of densified biomass.

However, another point of view was reported by Lund, Byme, Berndes and Vasalos (2015) regarding to mixing of biomass materials. They stated that the biomass materials are found to be difficult to be blended with either other types of biomass and/ or coal due to their different characteristics in terms of particle size, bulk density as well as flowability. Attempts on producing the biomass solid fuels with different biomass blend have been conducted by several researchers and different outcomes have been resulted.

In the research conducted by Rahaman and Salam (2017), it was proven that blending of sawdust with rice straw could significantly improve the physical characteristics of densified products for instance stable density and shatter index as well as requiring lower compaction pressure during densification process. In addition, Muazu and Stegemann (2015) suggested that briquettes could be formed by blending of rice husk with corn cob since there are problems with the usage of briquettes formed from these individual materials.

Rajaseenivasan and colleagues (2016) discovered that the neem powder is having higher binding capability as compared to sawdust, however vice versa in the case of calorific value. Hence, the addition of neem powder with sawdust significantly improves the durability index, shatter index, water resistance and impact resistance of the briquettes as illustrated in Figure 2.22.

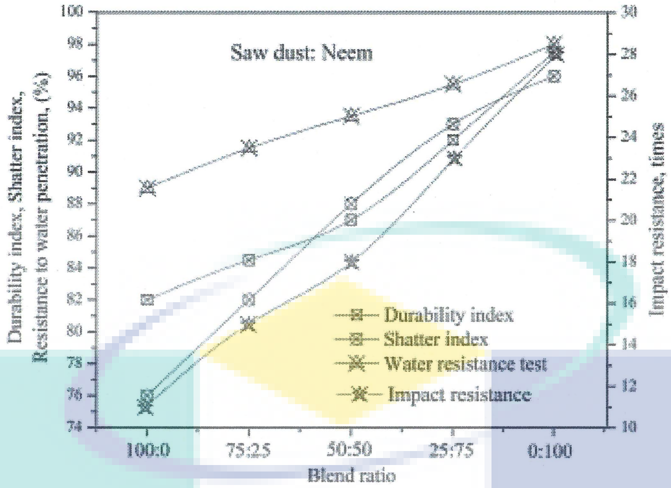


Figure 2.22 Properties of blended briquettes (saw dust: neem) with different ratio

Source: Rajaseenivasan, Srinivasan, Qadir & Srithar (2016)

Another example of research about the effect of mixing of materials to the strength of the densified products is from Islam, Hossain and Momin (2014), the compressive strength of the pellet formed from coir dust and rice husk blend with four different mixing ratios has been investigated as shown in Figure 2.23. A, B, C and D represent 80:20, 50:50, 40:60 and 20:80 of coir dust to rice husk whereas the control indicates pure rice husk pellet. At the end of the research, it was found that the compressive strength increased with increasing rice husk contents but lower in rice husk briquette.

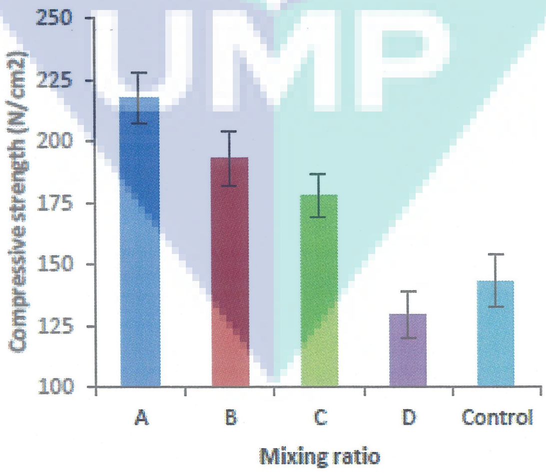


Figure 2.23 Compressive strength of different coir dust and rice husk blend briquettes at various mixing ratio

Source: Islam, Hossain & Momin (2014)

2.8.6 Holding time

Holding or dwell time, on the other hand is one of the important parameters in the briquetting process. Ndindeng et al. (2015) mentioned that there is research demonstrating that holding time in the range of 20 to 40 s can produce the briquettes with the least percentage relaxation with time. Another opinion from Wongsiriamnuay and Tippayawong (2015) stated that the compressive load is dependent on the specific pre-set pressure and it is usually held for 10 to 60 s to restrain the spring back effect, causing to the deformation of the briquettes. In the research of Adapa, Tabil and Schoenau (2009), the plunger was maintained at 30 s to produce the 6.3 mm pellets from different compacting pressures (31.6, 63.2, 94.7 and 138.9 MPa).

Bazargan, Rough and Mckay (2014) had conducted an experiment to figure out the effect of dwell time on the tensile crushing strength of the briquette. The result presented that there is no significant effect from the increasing holding time to the tensile strength of the briquettes. They also stated that the strength of the densified product would be affected by the manipulating dwell time at lower compacting pressure. This statement is confirmed by the other researcher, the density was increased by 14% at 10 s of holding time. For greater holding times, there is no further change in the density (Panwar, Prasad and Wasewar, 2011).

2.9 Study on combustion characteristics of biomass fuel

Besides the mechanical properties, the combustion properties of a biomass fuel need to be known before they can be used for any other applications especially energy generation. The common testing methods used to study the combustion phenomenon of the briquettes include proximate and ultimate analysis, calorific value determination as well as ash fusion (Boumanchar et al., 2016). A list of biomass fuel thermal properties analyses with its corresponding standard was mentioned in the research of Dermibas (2004) as shown in Table 2.13. These analyses are conducted by using the specific standard equipment. There is no fixed value for the following analyses; however they could be correlated with each other.

Table 2.13 Biomass fuel combustion properties analyses

Property	Analytical method
Heating value/ calorific value	ASTM D 2015, E 711
Particle size distribution	ASTM E828
Proximate composition	
Moisture	ASTM E871
Ash	ASTM D1102 (873 K), ASTM E830 (848 K)
Volatile matter	ASTM E872, ASTM E 897
Fixed carbon	By difference
Ultimate elemental	
Carbon, hydrogen	ASTM E 777
Nitrogen	ASTM E 778
Sulphur	ASTM E 775
Chlorine	ASTM E 776
Oxygen	By difference
Ash elemental	ASTM D3682, ASTM D2795, ASTM D4278, AOAC 14.7

Source: Dermibas (2004)

From the ultimate analysis, Carbon (C), Hydrogen (H), Oxygen (O), Nitrogen (N) and Sulphur (S) could be obtained. The concentrations of C, H and O could help in the estimation of heating value for the oxidation of these elements will result in more quantity of energy during combustion (Forero-Nuñez, Jochum and Sierra, 2015). However, the percentage of N and S within the solid fuel provides the information on the environmental impact. As reported by Jittabut (2015), a biomass consists of larger percentage of carbon, hydrogen and oxygen whereas a small portion of nitrogen and sulphur.

As for the case of proximate analysis, the results may help in the combustion phenomenon studies. For example, ignition and combustion problems could be resulted from high ash contents. Besides, the heating value increases with increasing fixed carbon and volatile matter. Also, the moisture content of the densified biomass could negatively affect the heating value and therefore trigger to the combustion problems (Saidur et al., 2011; Boumanchar et al., 2016). As reported by Rezania et al. (2016), high volatile matter of the biomass briquette will cause it to have faster combustion rate during the devolatisation process which makes it easy to be ignited and burnt.

The calorific value or high heating value represents the quantity of energy produced when the fuel is burned and normally the result is determined experimentally by using an adiabatic bomb calorimeter (Zhou et al., 2015; Boumanchar et al., 2016). Besides that, heating value also can be determined theoretically from the results obtained from proximate and ultimate analysis by correlating to each other. Several researchers (Yin, 2011; Callejón-Ferre et al., 2011; Shi et al., 2016) had developed the prediction equations and empirical formula/correlation to estimate the heating value. The equations have been established based on the lignin and hemicellulose contents (Boumanchar et al., 2016).

As stated in DIN 51731, 17500 kJ/kg is the minimum requirement for the commercial briquette. In the research done by Jiang and colleagues (2014), it was found that the calorific value of pellets was independent of process parameters (pressure, temperature and moisture content), but was highly affected by the heating value of raw materials and the amount of sludge added. Therefore, mixing of different biomass residues will influence the final value. Figure 2.24 illustrates the calorific value of the solid fuel produced from different blend ratio of saw dust and neem powder. It was found that the calorific value of the densified biomass materials increased with the decreasing weight ratio of neem powder.

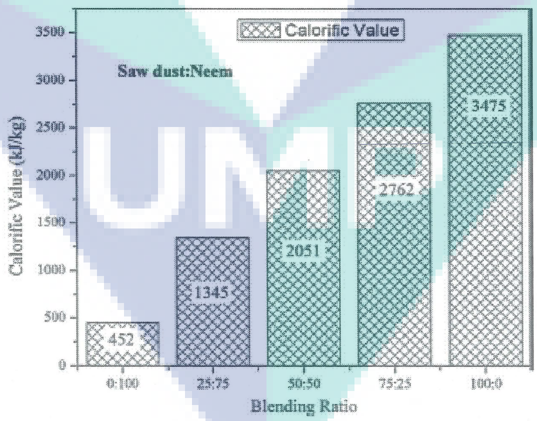


Figure 2.24 Calorific value of materials at different blend ratio
Source: Rajaseenivasan, Srinivasan, Qadir & Srithar (2016)

The burning efficiency of the biomass solid fuel could be identified through the water boiling test, in which the solid fuel is burnt to bring a pot of water to boil. With the application of this particular experimental testing, Rajaseenivasan and colleagues (2016) are able to figure out the time used to boil (min) and specific fuel consumption.

Time used to boil is the time required by the water to reach the boiling point whereas specific fuel consumption refers to the amount of fuel required to reach the boiling stage of one kg of water. At the end of research, it is observed that the time required for boiling as well as specific fuel consumption increases with the increase in neem blended briquette.

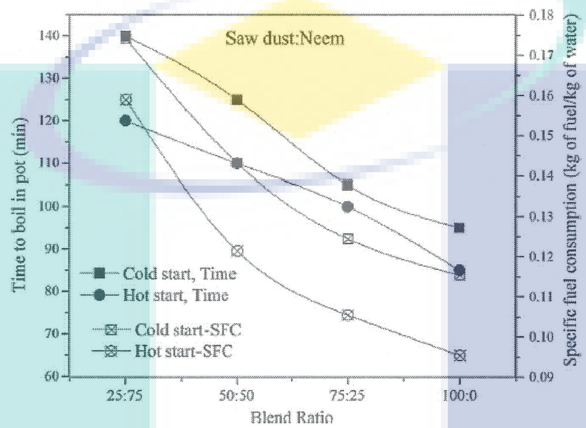


Figure 2.25 Variation of specific fuel consumption and time to boil for various blend ratio

Source: Rajaseenivasan, Srinivasan, Qadir & Srithar (2016)

On the other hand, the combustion characteristics of biomass fuel such as burning rate, heat release and ash content could be identified through the combustion test. There are two different formulas used to calculate the combustion rate and heat release which are adopted in the research of Faizal et al. (2010) as shown below:

$$Combustion\ rate\ \text{(g/min)} = \frac{Total\ Mass\ of\ Burnt\ Briquettes}{Burning\ Time} \qquad 2.1$$

In the following equation, the calorific value of the briquette needs to be determined prior to obtain the heat release of the briquette. This indicates that the calorific value as well as the combustion rate of the briquettes will affect the final value of the heat release for energy generation.

$$Heat\ release\ \text{(W)} = Calorific\ value\ x\ Combustion\ Rate \qquad 2.2$$

2.10 Summary of literature study

Agricultural residues have been targeted in bio-energy production for this category of biomass does not threaten the food security. In Malaysia, there are abundant agricultural wastes left and burnt in field which could be used for heat and energy production. Therefore, the selected biomass wastes in this study are rice husk, sugarcane bagasse and spent coffee ground.

Briquetting technology is claimed to be one of the best alternatives to resolve the problems associated with the use of original raw biomass. The technologies, types of solid fuel and binding mechanism had been reviewed and become the fundamentals to the designed briquetting facility for biomass briquette formation in this study. In addition, the briquetting parameters as well as the factors affecting the strength and durability of the solid fuel act as a benchmarking which subsequently can aid in the research methodology design.

The mechanical properties as well as combustion properties analyses on the biomass solid fuel reviewed would be referred in the following methodology design to investigate the potential of selected biomass residues in solid fuel formation.

CHAPTER 3

METHODOLOGY

3.1 Overview

This chapter provides a clear insight on the research methodology applied to achieve the objectives in this project. The research study was initiated with the waste biomass selection where three types of agricultural residues were chosen, namely rice husk, sugarcane bagasse and spent coffee ground. The raw materials were first dried to a moisture content ranging from 8 to 15% and subsequently ground to powder with the grinding speed from 500 rpm to 580 rpm.

Prior to the briquetting process, refinement on the briquetting facility was necessary to accommodate the requirement of the briquette formation. The facility refinement was done in accordance to the final shape of the briquette to be produced in this study. Then, biomass briquettes were generated with the three respective residues through the manipulation of the compacting pressure ranging from 200 to 300 bars, at an interval of 50 bars whereas the preheating temperature was 120, 150 and 180°C.

The briquettes formed were inspected and filtered before the analyses could be done. In the first stage of analysis, the mechanical strength of the briquettes formed with single residue would be analysed accordingly. The analyses covered four tests which were drop test, immersion test, tumbling test and compression test. After that, the optimal briquetting parameters were selected for the production of briquettes from different biomass blends and weight ratio. In the second stage of analysis, the briquettes with different biomass combination, coupled with 4 different mixing ratios would be analysed in terms of mechanical strength as well as the combustion characteristics.

The combustion characteristics tests included bomb calorimetry analysis, ultimate analysis as well as water boiling test. Water boiling test eventually would aid to determine the thermal efficiency, power output, specific fuel consumption and burning rate of the biomass briquette formed using specific formulae. With all the analyses done on the briquettes, the optimal blends ratio and the biomass blends would be selected. The methodology flow for the briquette formation and relevant analyses could be briefly described in Figure 3.1.

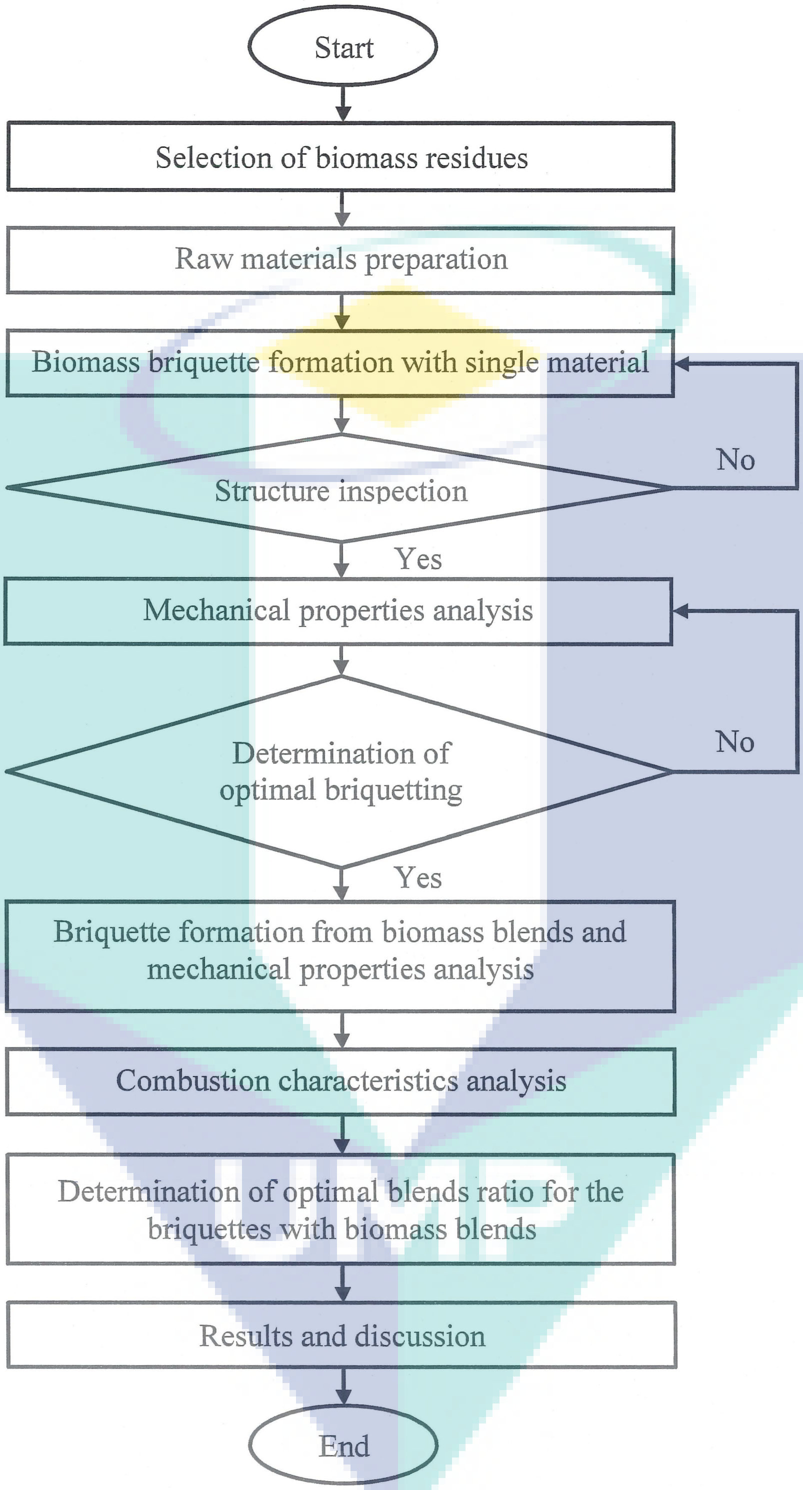


Figure 3.1 Methodology flow chart

3.2 Biomass Residue Selection and Collection

The availability, supply as well as the potential of biomass wastes to be used as the renewable feedstocks in Malaysia for briquette formation was reviewed in section 2.1. The agricultural residues were chosen due to its substantial quantities and sustainability in Malaysia and at the same time could be easily accessed near the research area. Besides oil palm wastes, there are other types of agricultural residues having potential to be converted into solid fuel for energy generation. Therefore, the raw material opted in this research for solid fuel production is listed as follows:

a. Rice husk,
b. Sugarcane bagasse,
c. Spent coffee ground.

The rice husk was collected from Sekinchan, Selangor where the rice bowl of Malaysia is located. From the stalls selling sugarcane juice, a sufficient supply of sugarcane bagasse could be accumulated. Meanwhile, the spent coffee ground from Starbucks coffee Kuantan that are given away as garden fertiliser had been collected for the biomass solid fuel formation. All the accumulated biomass feedstocks were free of charge for they were normally available in huge amount and discarded as wastes after rice harvesting, juice and coffee extraction.

3.3 Dehumidification and Size Reduction

The collected waste biomass would normally come with high moisture content as well as in bulky, wet and loose form which could not be directly briquetted into a solid fuel. The high moisture content of the raw materials might trigger to the poor grindability and also a higher energy requirement for size reduction (Liu and Han, 2015). Therefore, drying in this case was essential to reduce the moisture content of the raw material in a certain range. In this study, two methods are applied: sun dried and oven dried. Excluding rice husk, all the raw materials are dried under the hot sun for at least one day and heated in the oven at 80-100°C for an hour until a satisfactory range of moisture content was achieved. A moisture meter was used to check the moisture content of the residues was in a range of 8-15%.

The subsequent process would be size reduction, which could help to increase the biomass pore size and the total surface area too for binding purpose (Strezov and Evans, 2015). The dried materials, except the spent coffee ground, were reduced in size by using a specifically designed grinding facility as presented in Figure 3.2, equipped with four pairs of shear and hammer mill screen size of 2.0 mm. The grinding speed of the facility ranged from 500-580 rpm, varying with different materials and as the result a finer and even powder-form particles were obtained. A mixture of various sized particles could give optimal solid fuel quality which might lead to inter-particle bonding with nearly no void spaces (Missagia et. al, 2011).

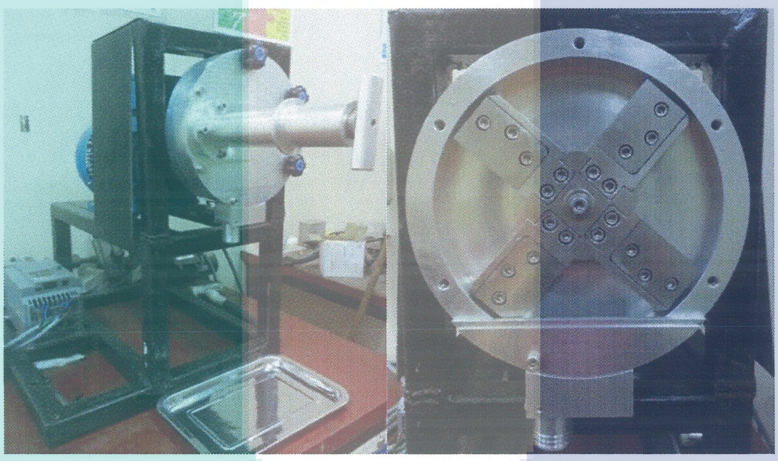


Figure 3.2 Grinding facility for rice husk and sugarcane bagasse

The ground biomass residues were portrayed in Figure 3.3, indicating rice husk, sugarcane bagasse and spent coffee ground.

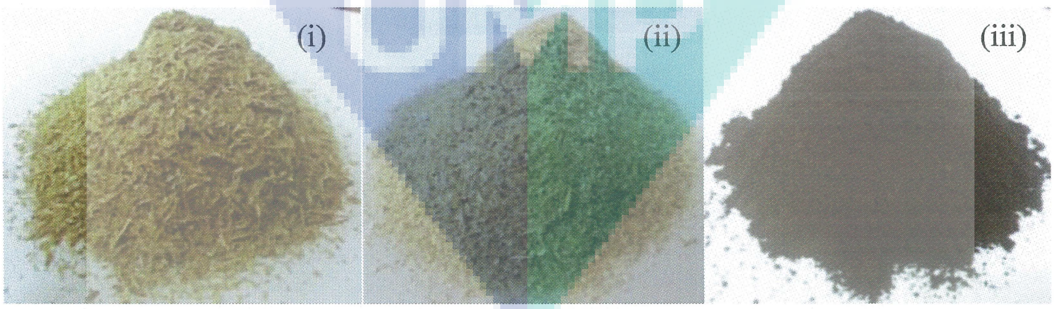


Figure 3.3 Ground raw materials of (i) rice husk; (ii) sugarcane bagasse; (iii) spent coffee ground

Figure 3.4 shows the ground materials filled in air tight plastic bag right after grinding process. The packaging is crucial to restrain the surrounding air moisture and impurities from being absorbed by the ground wastes that might affect the quality of briquettes formed later.

Figure 3.4 Packed ground feedstocks

3.4 Production of biomass briquette without blending

In this section, the shape of the briquette formed was determined and the specific piston and mold set were designed and fabricated to accommodate the requirement for briquette formation. In the first set of experiment, rice husk, sugarcane bagasse and spent coffee ground were briquetted individually at three different preheating temperatures and compacting pressures respectively. The briquetting process including the relevant parameters used would be further described in the following section.

3.4.1 Biomass Briquetting Facility

The shape of the densified product to be formed must be decided before briquetting could be done. Determination of the briquette's shape was aimed to accommodate with the readily available facility as to reduce the fabrication cost. The readily hand operated hydraulic press with the integration of simple hydraulic system could be used for the briquette production, yet refinement was required in the compaction section particularly. Figure 3.5 briefly explains the flow of the facility refinement.

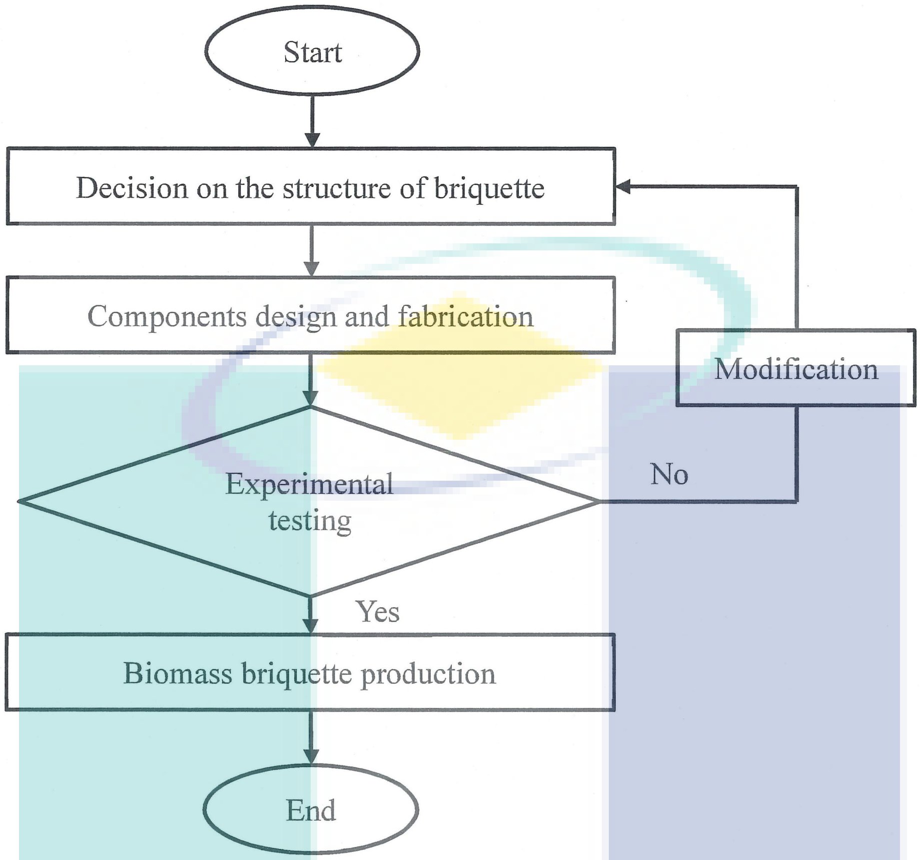


Figure 3.5 Flow of the facility refinement

The initial idea for the briquette's shape originated from the factsheet of Clarke, Eng and Preto (2011), they mentioned that the biomass puck was more resilient to moisture. Despite having similar density with pellet, the production cost for this particular densified product was lower. Hence, the structure of the briquette in this study was decided to take the shape of hockey puck with 50 mm in outer diameter. At the same time, similar briquette structure was also adopted by Hassan, Kee and Al-kayiem (2013) as well as Chin and Aris (2013) to produce solid fuel from oil palm wastes.

A new set of densifier mold, piston and locking pin was then designed and fabricated according to the desired briquette's structure. All the components were designed to be detachable in order to ease the removal of the briquette and the cleaning work after each briquetting process as well as minimising damage to the components. Due to the involvement of heating during densification, installation of heating element was utilised as the heat source and thus a unit of heating cylinder was designed to be slotted into the densifier mold. The outer wall of heating cylinder was then encircled with the oven heating element in order to heat up the sample during compaction. Figure

3.6 depicts the design and prototype of the components for the biomass densification whereas the densified product is shown in Figure 3.7.

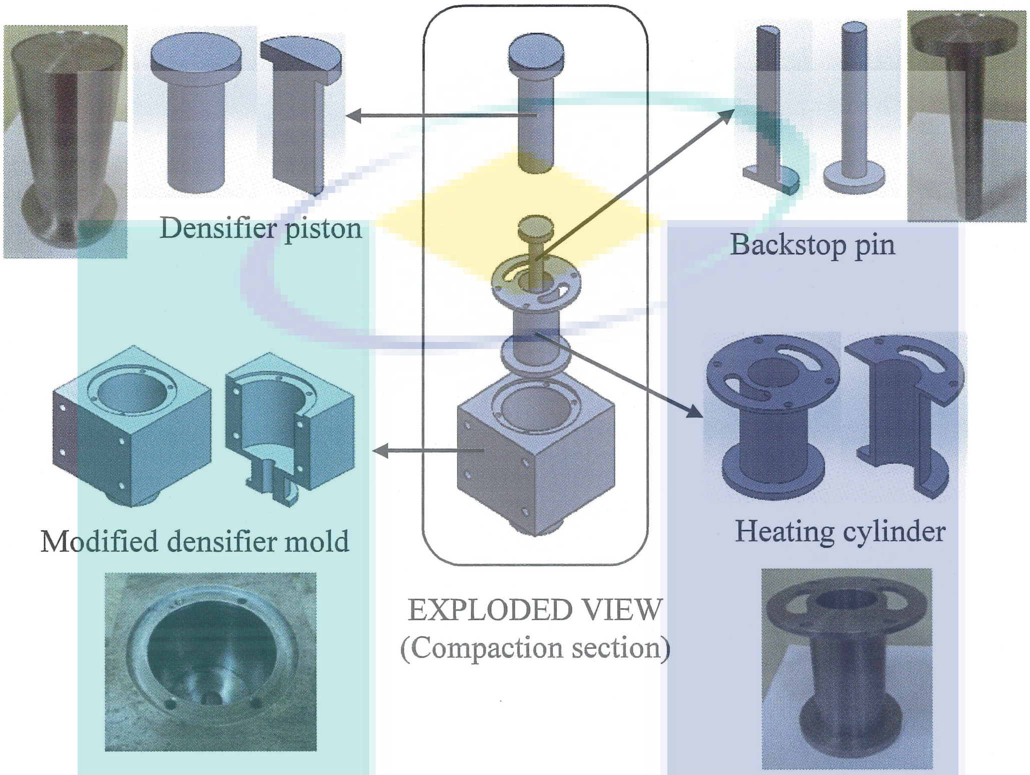


Figure 3.6 The first design and prototype of the components

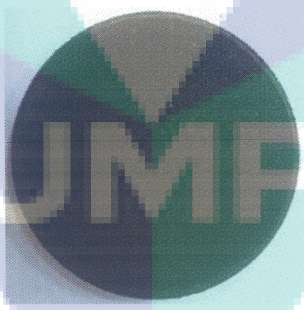


Figure 3.7 Puck briquette

3.4.1.1 Preliminary testing and modification of the fabricated components

The assembled densifier unit was tested through the preliminary experiment by producing the designed briquette. According to Yank, Ngadi and Kok (2016), the briquette was suggested to be enhanced by adding a 15 mm diameter hole at the centre which assembling as a doughnut liked briquette. The middle hole was made to increase porosity and oxygen supply to enhance the combustion of briquettes.

In conjunction with the changes made on the biomass structure, the piston and locking pin were re-designed and fabricated. In addition, a minor modification was done on the densifier mold by eliminating the extruded feature at its bottom part in order to accommodate the requirement of the briquette formation. Besides that, four M8 holes were made on the bottom surface of the mold for the portable stove installation.

The latest design and prototype of the components with the exploded view and the latest briquette structure are illustrated in Figure 3.8 and Figure 3.9, respectively.

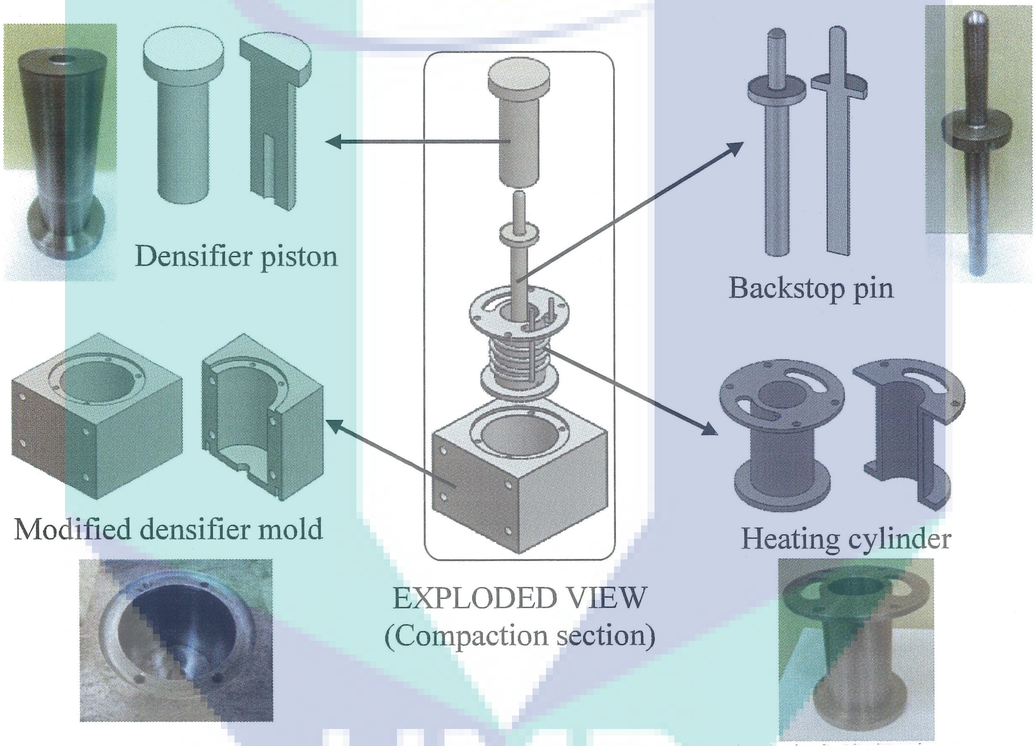


Figure 3.8 The latest design and prototype of components

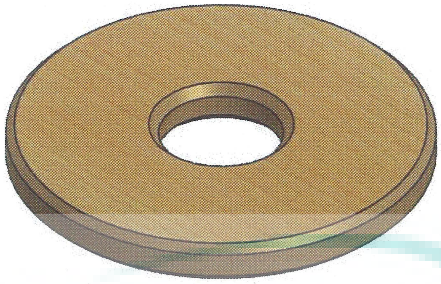


Figure 3.9 Doughnut shaped briquette

Experimental testing had been conducted on the compaction unit with the installed heating element and connected electrical circuit as illustrated in Figure 3.10. The result showed that the installed heating element could only be heated up to approximately 300°C. However, the maximum temperature recorded was only 80°C at the bottom of the heating cylinder where the sample was placed. The temperature was not high enough as desired for the briquette formation in this study. Besides that, distraction has been created with the installation of the electrical circuit and it might also impose danger to the operator while briquetting was carried on.

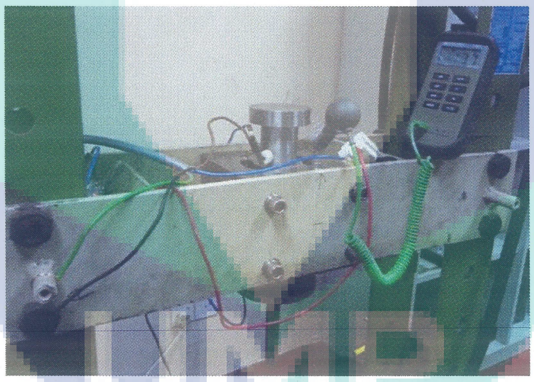


Figure 3.10 Preliminary testing on heating element operation

As a result, the installation of heating element was considered not feasible in this briquetting densifier and thus the device for heat source was replaced. A portable gas stove was then installed below the mold. With that, direct heating would focus to the base of the mold, where the samples are located nearly, and at the same time a thermocouple wire was fixed to a 3 mm hole positioned at 12 mm from the base of the heating cylinder (Figure 3.11) to observe the temperature change during compaction.

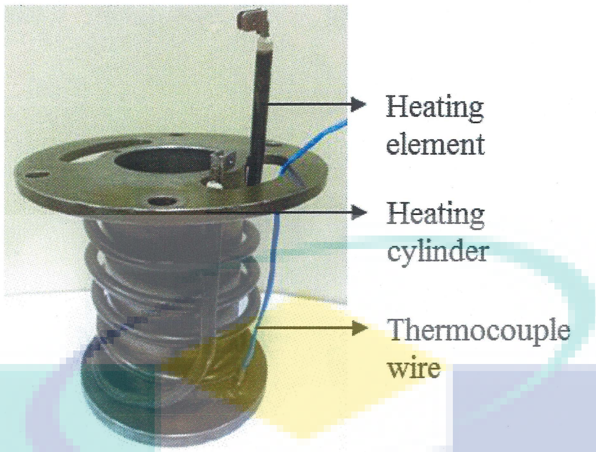


Figure 3.11 Heating cylinder with thermocouple wire installation

With the minor refinement on the briquetting facility including the replacement of a new hydraulic pump, the latest set-up of the briquetting facility was portrayed in Figure 3.12.

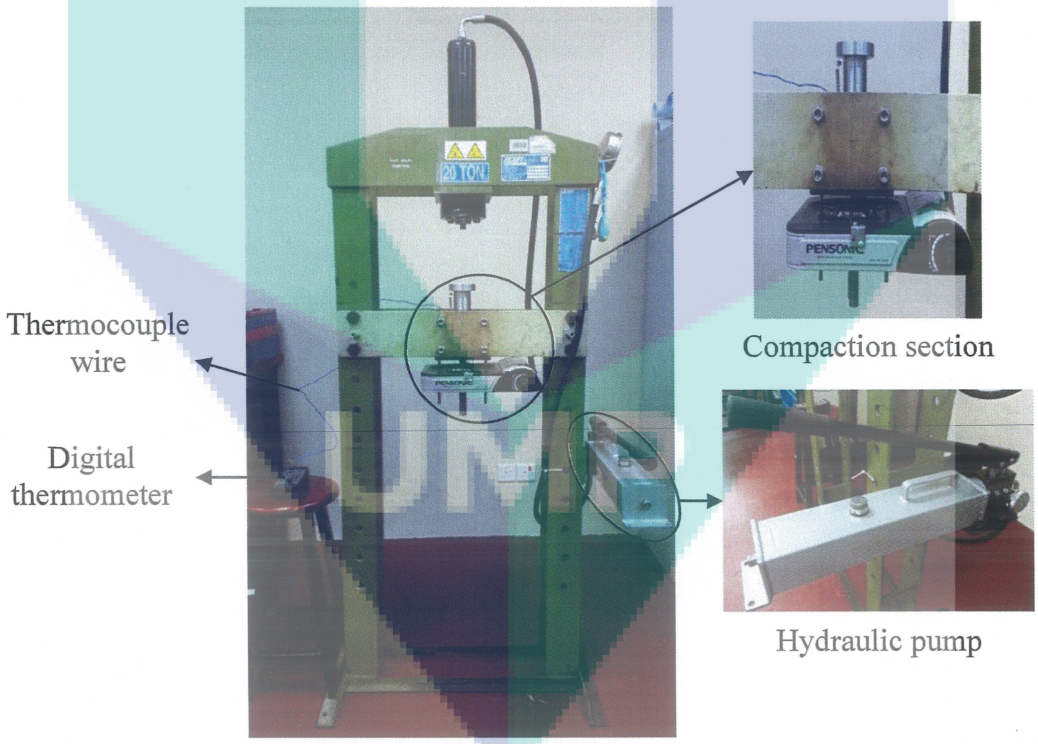


Figure 3.12 The latest briquetting facility

3.4.2 Briquetting Process

The briquetting process was conducted to increase the energy density of the loosely-bounded waste materials and thus resolve the problems of storage, transportation as well as handling. Basically, briquetting was a process to compact the ready ground biomass residues into solid form under the pre-determined compacting pressure and temperature as well. The briquetting process was carried out in a closed room with constant airflow and only during daytime without raining because higher environmental humidity might affect the quality of the briquettes and also the final data.

In this research, there was a simple briquetting process applying for all the briquettes formed from different biomass feedstocks. Figure 3.13 briefly presents the flow of the briquetting process and the detailed methodology would be explained in the subsequent sections.

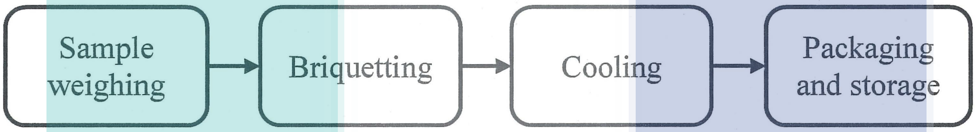


Figure 3.13 Flow of briquetting process

3.4.2.1 Sample weighing

Approximately 10 g of ground materials were weighed by using a weighing scale with the accuracy up to 0.01 g. This particular sample mass was adopted throughout the research since it was the minimum mass for the formation of briquette with acceptable thickness and could sustain in shape. The briquettes were formed from the blend of rice husk and bran with the addition of binders (Yank, Ngadi and Kok, 2016) was illustrated in Figure 3.14, with about 64 mm in height. However, there were crack lines on the surface of the briquette, indicating the lower strength of the densified products due to its larger thickness. Therefore, additional masses were not deemed necessary in this research to avoid wastage on biomass resources. Also, the mass fixed was supported by the research of Hassan, Kee and Al-kayiem (2013) as well as Chin and Aris (2013) whereby 10 g of materials were used for briquette production.

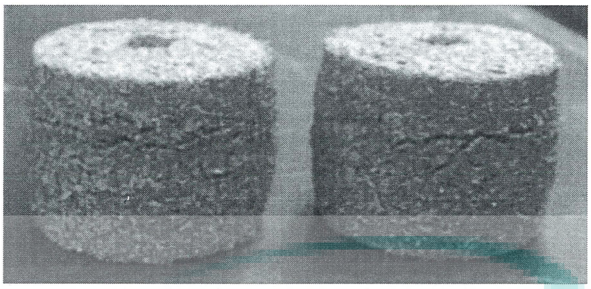


Figure 3.14 Briquettes formed from rice husk and bran
Source: Yank, Ngadi and Kok (2016)

3.4.2.2 Determination of briquetting parameters

As acknowledged, briquetting could be done with or without the addition of binders under certain level of pressure. Heating the biomass during densification might soften the lignin in the plant residues which acts as the natural binder to enhance the binding process (Adapa, Tabil. and Schoenau, 2009). Therefore in this research, the compacting pressure and preheating temperature were incorporated in the briquetting process with no binders added.

In accordance to the specification of the briquetting facility, the maximum pressure could be reached by the hydraulic press was 400 bars. On top of that, the minimum pressure required for the briquetting facility to form a briquette was 200 bars, which had been verified through the preliminary testing. Hence, the compacting pressures were decided to be 200, 250 and 300 bars for the briquettes formation. Since self-binding briquetting technique was adopted as well as the incorporation of heating in the process, these particular medium pressures could be used to produce briquettes with adequate strength.

Lignin owned the thermosetting properties and a low melting point of about 140°C (Adapa, Tabil. and Schoenau, 2009). In addition, too high of temperature was not suggested as the biomass might be dried up, causing blockage of the materials inside the die and thus reducing the durability of the sample product (Wongsiriamnuay and Tippayawong, 2015). In this research, three different biomass feedstocks with different characteristics were involved and at the same time the application of medium compaction pressure. The formation of briquettes was optimised at three different temperature levels, ranging from 120 to 180°C at an interval of 30°C.

3.4.2.3 Briquetting

The briquetting process starts with the facility setup, where the detachable components are assembled and the thermocouple wire was connected to the digital thermometer placed in a static bench. The portable stove was then ignited. At the same time, the weighed ground materials were then poured into the heating cylinder when the thermometer shows 10°C before the pre-determined temperature. The piston was then slotted into the heating cylinder.

When the thermometer showed 1°C higher than the desired temperature, the stove was turned off and then the hand pump was actuated until it achieved the desired compacting pressure, as shown in the pressure gauge. The temperature was maintained at 120°C throughout the densification process. The illustration of briquetting process is shown in Figure 3.15.

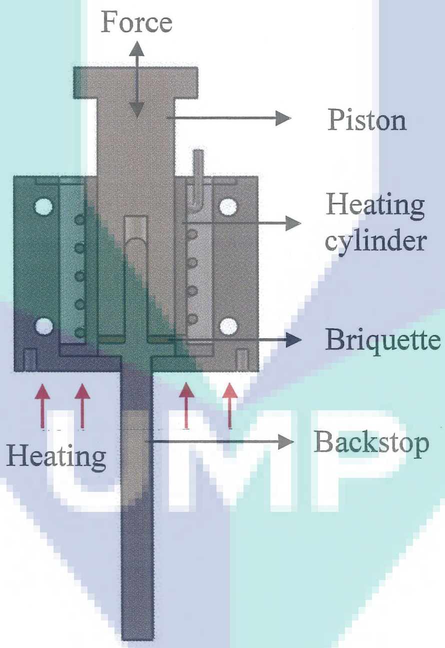


Figure 3.15 Illustration on briquetting process

A constant dwell time of 30 s was fixed for each densification process. The holding time fixed was supported by Ndindeng et al. (2015) that the briquettes produced with the holding time from 20 to 40 s were having least percentage relaxation. In addition, Wongsiriamnuay and Tippayawong (2015) stated that 10-60 s of holding time could prevent the spring back effect after compaction.

The example of rice husk briquette formed as depicted in Figure 3.16 was in line with the design of the densifier unit (piston and mould) which is easy to be handled, in the sense of placement and stacking in a storage box or on a tray. Also, this particular design enabled the briquettes to withstand a certain amount of external pressure and thus would not disperse easily. The briquettes formed with three different residues were replicated according to the level of process variables listed in Table 3.1 as well as the types of analysis needed.

Figure 3.16 Example of briquette formed

Table 3.1 Briquetting parameters

Preheating temperature (°C)	Compacting pressure (bar)
120	200
	250
	300
150	200
	250
	300
180	200
	250
	300

3.4.2.4 Physical inspection of the briquette structure and storage

After the briquetting process, the structure of the formed briquettes was inspected with respect to its shape sustainability. There were possibly cracks, broken edges or irregular in shape and only those briquettes with good structure would be selected for the subsequent testing. Figure 3.17 portrays one example of rejected briquette with cracks.

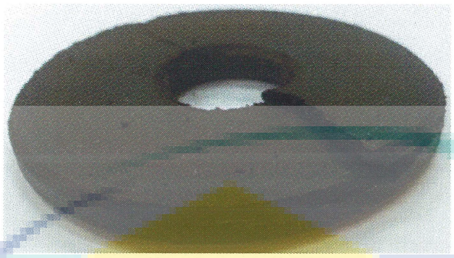


Figure 3.17 Example of briquette with defects

The briquettes extracted from the mold were normally hot and plastic, thus they were placed aside for cooling. The briquettes were then stored in the containers with labels and kept at room temperature to obtain rigidity and stability. This particular step was meant to restrain the surrounding air moisture which might affect result of the subsequent analysis result.

3.5 Briquette formation from biomass blends

Mixing or biomass blending was meant to enable the selected biomass residues complementing each other with respect to their respective characteristics. Meanwhile, the mechanical properties as well as combustion properties of the briquettes could be enhanced by adding in other types of biomass residues. In this project, three types of biomass mixture were prepared: rice husk and sugarcane bagasse, rice husk and spent coffee ground as well as sugarcane bagasse and spent coffee ground. The biomass materials were blended according to the mixing ratio, as listed in Table 3.2, summed up to about 10 g of mixture. The decision making on the mixing ratio in this experiment referred to the research done by Jittabut (2015) in the physical and thermal properties study of the briquette fuels from rice straw and sugarcane leaves. On top of that, Kaliyan and Morey (2009) revealed that >20% by weight of binding feed ingredient or biomass material must be blended with the base feed in order to obtain an equal amount of solid fuel durability compared to that of chemical binders (<5% by weight).

Table 3.2 Biomass blend with the corresponding mixing ratio

Biomass blend	Mixing ratio (wt.%)
Rice husk : sugarcane bagasse	80:20 60:40 20:80 40:60
Rice husk : spent coffee ground	80:20 60:40 20:80 40:60
Sugarcane bagasse : spent coffee ground	80:20 60:40 20:80 40:60

The briquettes with biomass blend were formed at a constant preheating temperature and compacting pressure which would be decided through the first stage of analyses.

3.6 Sample Analysis

In this research, two different types of briquettes had been produced, without blending and dual residues blending. The former would be produced at manipulated briquetting parameters whereas the later was formed at the optimised briquetting parameters selected through the analyses. There were two different categories of analyses namely mechanical properties and combustion characteristics.

In the first stage of experimental analysis, the mechanical properties of the briquettes from different residues resulted from the manipulated briquetting parameters were analysed individually. While for the second stage of analysis, the mechanical properties as well as the combustion characteristics of the briquettes with biomass blend including the selected pure residue briquettes would be analysed accordingly. The significance of the mechanical properties and combustion characteristics of the briquetted biomass had been reviewed in the earlier chapter. The methodologies of analyses would be described in detail in the following sections.

3.7 Mechanical properties analysis

The significance of the mechanical properties analyses were reviewed accordingly in Section 2.7. The densified product that could fulfil the consumer requirements as well as market standards would indicate the success of densification process and quality solid fuel production. Therefore, the mechanical properties of the briquettes were investigated in terms of strength, durability as well as water absorption capacity. As summarised by Kaliyan and Morey (2009), there are four relevant analyses namely shatter resistance, abrasive resistance, compressive resistance and water resistance test. These experimental testing could help to measure the effectiveness of the inter-particle bonds formed during the briquetting process.

In addition, these analyses are first conducted to investigate the effect of compacting pressure ranging from 200 to 300 bars and temperature from 120-180°C to the mechanical strength of the briquettes formed from the selected residues individually/ without blending. On top of that, a similar analysis would be conducted to determine the mechanical properties of the briquettes formed with biomass blend too.

3.7.1 Shatter Resistance Test

The shatter resistance (impact resistance) analysis was also known as drop test in a simple meaning. It might help in simulating the forces encountered when emptying the briquettes from trucks onto ground, or shifting from one place to another (Kaliyan and Morey, 2009). On top of that, the safe height of briquette production also could be determined through this particular experiment testing.

In this study, the analysis was conducted to figure out the hardness of the briquettes with respect to the manipulation variables, including the compacting pressure and temperature according to the types of residue. The higher impact resistance indicates the better binding performance of the briquette formed.

The method adopted in the research done by Sengar et al. (2012) and Birwatkar et al. (2014) was selected in this study. The sample was dropped onto the concrete floor from 1 m high for 10 times continuously. The table top with an adjustable platform together made up the designated height of 1 m, as illustrated in Figure 3.18.

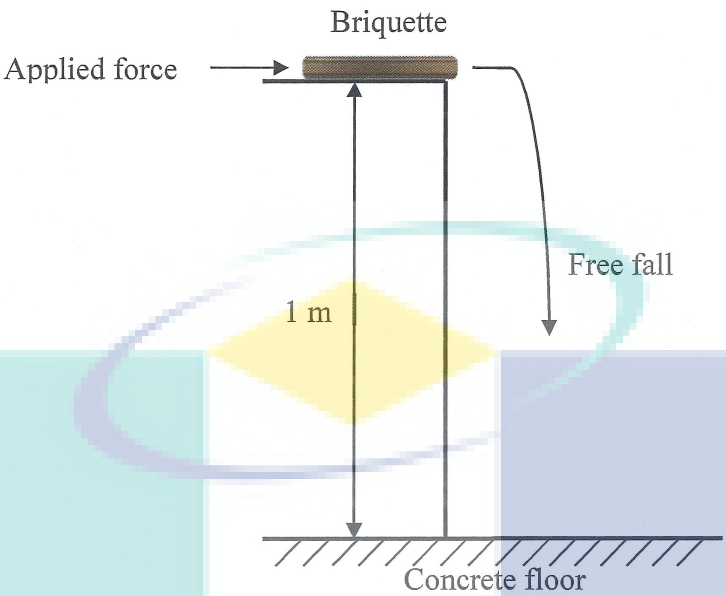


Figure 3.18 Schematic diagram of drop test

The weight of briquette was recorded and images were snapped too before and after shattering. The higher strength briquette might experience the least weight loss in this analysis. Each briquette from the individual variable was replicated for three times. The percentage of the weight loss and impact resistance was calculated by using the following equations.

$$Percentage\ of\ weigt\ loss\ (\%) = \frac{W_1 - W_2}{W_1} x\ 100\% \tag{3.1}$$

$$Impact\ resistance\ (\%) = 100\% - percentage\ of\ weight\ loss(\%) \tag{3.2}$$

3.7.2 Abrasive Resistance Test

The abrasive resistance test, also known as tumbling test was the measure of the mechanical durability of densified products in consequence of transport and handling processes. The briquette was subjected to controlled shocks by collision of fuel particles against each other's and against the walls of a rotating chamber. Kaliyan and Morey (2009) also mentioned that the higher the durability, the higher quality the densified product is where this concept was applied in the feed pelleting industry.

This analysis would evaluate the durability of the briquettes formed from three set of briquetting variables. The significance of the manipulation on compacting pressure and preheating temperature to the durability of the briquettes would be analysed through the results obtained.

Since there was none of any standard equipment available in the research area, a simple tumbling can was constructed by referring to the standard EN 15210-2:2011 which was meant for solid fuel briquettes (Repsa, Kronbergs and Pudans, 2014). A cylindrical drum with 15 cm diameter and 18 cm height was used as the tumbling can with a solid aluminium rod attached to its base. Besides that, a piece of metal plate was attached to the inner wall of the can, acting as the baffle for the tumbling process.

The tumbling can was first fixed to the chuck of the conventional lathe machine. Three samples were then placed into the can and the cover lid was put on before experiment started. The tumbling process was conducted with the speed rate of 25 rpm for 5 minutes in clockwise direction by referring to the standard of EN 15210-2 (2010). Sieving was required before and after tumbling for 30 seconds to remove the fines attached to the sample. The illustration of the tumbling test was displayed in Figure 3.19.

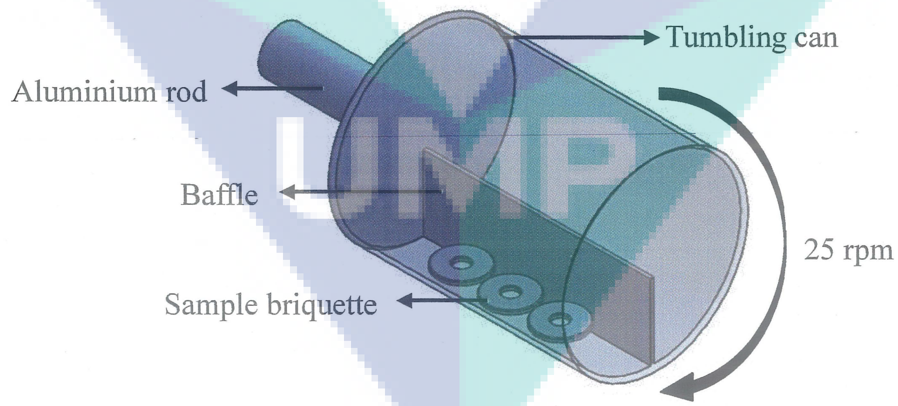


Figure 3.19 Schematic diagram of tumbling test

The initial and final weight of those samples after tumbling was recorded. The percentage of abrasion resistance was calculated by using the formulae as follows:

$$Percentage\ of\ weight\ loss\ (\%) = \frac{W_i - W_{ii}}{W_i} x\ 100\% \quad 3.3$$

$$Abrasion\ resistance(\%) = 100 - Percentage\ of\ weight\ loss(\%) \quad 3.4$$

3.7.3 Compressive Resistance Test

The strength of the briquettes formed from different residues and manipulation variables was once again evaluated through the compression resistance test. This particular test was known as diametrical compression test where load was applied to the sample between two flat and parallel plates until it failed by cracking or braking (Kaliyan and Morey, 2009). According to Maraver et al. (2015), determination of briquette compressive strength or hardness was indeed important for storage and feeding processes, but it was not limited by standard.

This compression test could help in simulating the possible stress/ load applied to the briquettes in axial direction. Meanwhile, the internal bonding strength of the briquettes formed from 120-180°C and 200-300 bars would be analysed according to the residue types. Thus, higher compressive strength implies a good inter-bonding between particles within the solid fuel formed.

The compression test was conducted by using an Instron model 3396 Universal testing machine (Figure 3.20) with a load cell capacity of 100 kN and equipped with the Bluehill 3.0 software to monitor the compression test. The cross-head speed was 0.50 mm/min, where each compression test could be done within 5 minutes. The recorded result was expressed in load at maximum compressive load (N).

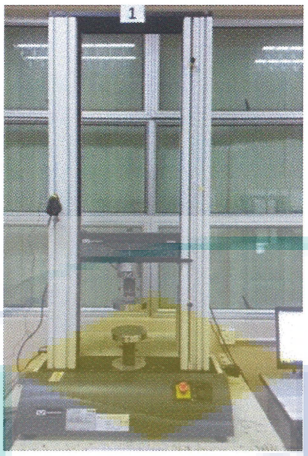


Figure 3.20 Instron universal testing machine

Due to the smaller thickness of the briquette, a support fixture was built to place the briquette in vertical position for compression purpose; the briquette was placed in the cleft of the fixture and locked into position by screwing the two L-shape plate. A sample of briquette to be tested was placed horizontally in the compression test fixture and load was applied by the device until the briquette failed by cracking. Figure 3.21 portrayed the diametrical compression test.

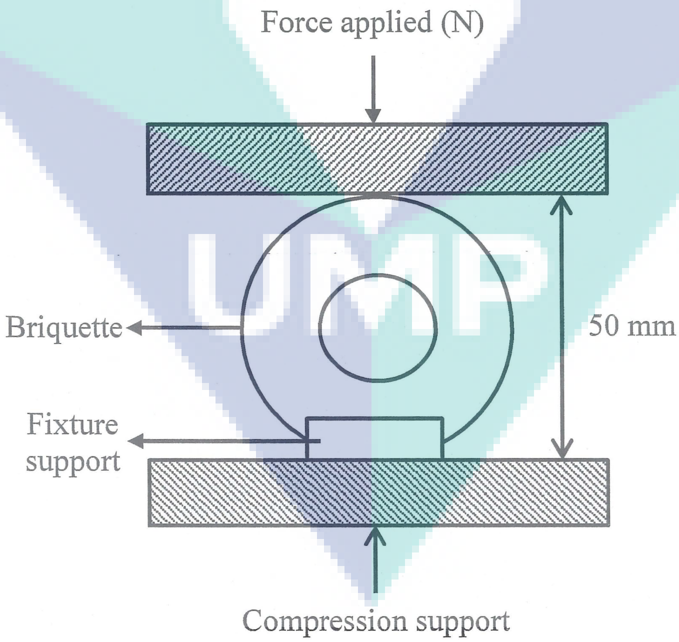


Figure 3.21 Diametrical compression test

3.7.4 Water Resistance Test

The quality of the briquettes would be affected if they are exposed to rain or being stored and transported under high humidity conditions. Other than implying forces to the briquettes for strength determination, water permeability is also one of the crucial aspects to be considered especially when dealing with storage, transportation and handling. The structure could not sustain in shape and crumble easily due to the weak inter-bonding, and thus creating problem to the combustion.

This particular analysis was different from the previous analyses where the strength of the briquettes formed from different manipulation variables might deviate when exposed to water. In this particular test, higher water resistance indicates the suitability of that particular briquette to be used in a high humidity environment. Certain densified product might expand when exposed to water and the moisture content would cause to the ignition problem as well.

A 200 ml beaker was filled with 100 ml of tap water at room temperature as portrayed in Figure 3.22. The initial weight of each briquette was recorded before the immersion. At the same time, a stopwatch was used to record the immersion duration at 30 seconds. This immersion procedure was performed according to the research done by Davies and Davies (2013).

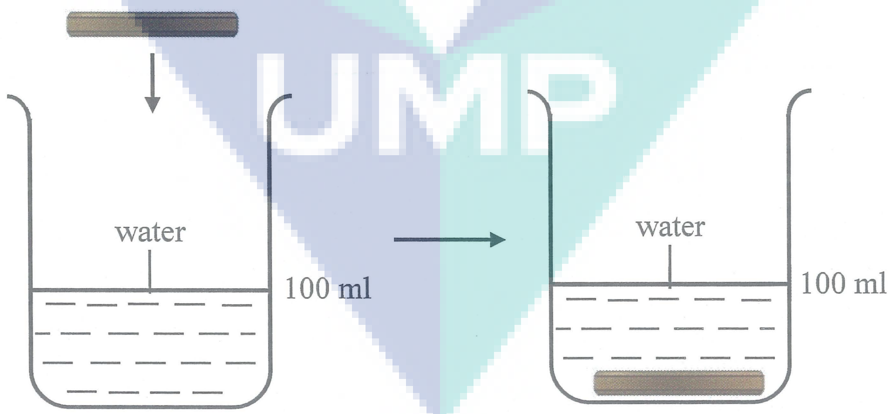


Figure 3.22 Briquette immersion test

After the immersion, the briquette was extracted from the beaker and the final weight was obtained. The percentage of water gained by each briquette was calculated by using the equations as followed:

$$Percentage\ of\ water\ gained(\%) = \frac{W_b - W_a}{W_a} x\ 100\% \quad 3.5$$

$$Water\ resistance(\%) = 100\% - percentage\ of\ water\ gained \quad 3.6$$

3.8 Determination of briquetting parameters

In this particular section, the first stage of analysis was carried out to determine the optimal briquetting parameters used for the formation of briquettes with biomass blends in the consequent analysis. The mechanical properties of the rice husk, sugarcane bagasse and spent coffee ground briquettes would be analysed individually. The selected briquetting parameters: preheating temperature and compacting pressure might be able to produce the briquettes with adequate strength and durability according to the acceptance limit as mentioned in the literature.

3.9 Analysis on the Combustion Characteristics of Briquette

The analyses on the combustion characteristics are ultimate analysis, bomb calorimetry test and water boiling test. The briquettes formed with biomass blends as well as the corresponding pure residues briquettes would be involved. This particular analysis was meant to investigate the combustion behaviour as well as the thermal properties of the briquettes before they could be burnt to produce energy for heat or electricity generation.

3.9.1 Ultimate/ Elementary Analysis

Ultimate analysis is an estimation of chemical elements in the biomass briquette by using elementary analyser (Figure 3.23). The basic elements made up biomass include carbon (C), hydrogen (H), nitrogen (N) and sulphur (S). The rice husk, sugarcane bagasse and coffee briquettes formed from 150°C and 300 bars were sent for elementary analysis as the representative for all the other variables.

The concentrations of C and H in the briquettes should be higher as to aid in combustion and also contribute to higher calorific value. On the other hand, low nitrogen and sulphur content was desired as their reaction with water and oxygen might form acidic compound, for instance acid rain (Hassan, Kee and Al-Kayiem, 2013). The experiment was conducted in Central Laboratory at Universiti Malaysia Pahang, Gambang whereby the Dumas combustion method was employed in the CHNS analysis.

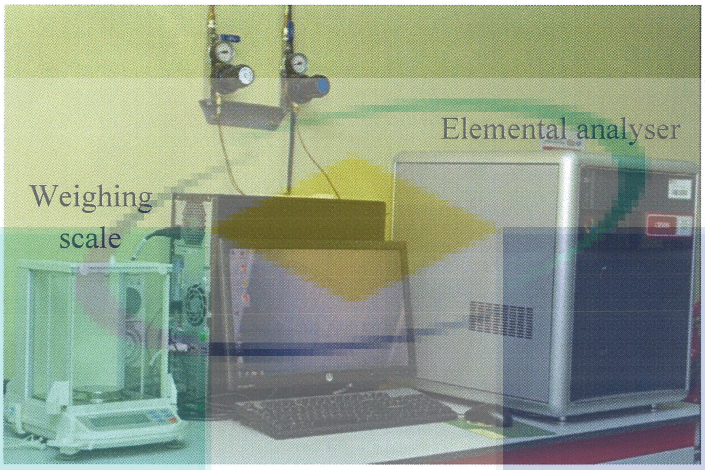


Figure 3.23 Elemental analyser in Central Laboratory, UMP Gambang

3.9.2 High Heating Value/ calorific value

High heating value or gross calorific value, measured in MJ/kg was the maximum amount of energy that could be extracted from the combustion of the briquettes. The heating value of the briquettes obtained in this section would help to identify the thermal efficiency of the briquettes with different biomass residues and its suitability to be a combustible fuel. The effect of applied pressure and temperature during compaction on the heating value of densified product could be identified through the analysis.

In conjunction with the testing and measurement of the high heating value of the sample, there was a complete system of Parr1341 Plain Oxygen Bomb Calorimeter available in Thermodynamics laboratory. Less than 1.0 g of briquette was allowed to be filled into the combustion capsule and weighed. The apparatus is set up accordingly with a proper Standard Operating Procedure (SOP) as listed in Appendix B. The similar procedure was repeated at least three times for each sample to obtain the average value.

3.9.3 Water Boiling Test

The combustion characteristics of the biomass briquettes could be further analysed through water boiling test. The Water Boiling Test (WBT) protocol version 4.2.2 was referred with a slight modification on the volume of water used for boiling for the weight of the briquette burnt is only around 10 g. According to Ugwu (2013), this particular water boiling experiment simulated the real cooking condition especially in typical rural households.

Due to the constraint regarding to the availability of a standard combustion stove in the research area, a simple biomass stove was built with two food cans and the wire gauge. The two cans were in different diameter and height. The body of these two cans were drilled with holes for better air and oxygen ventilation. The smaller can with the holes at the base and upper part of the body was then slotted into the bigger one. The wire gauge was cut and folded in size according to the space and placed into the can. The stove used for the water boiling test was illustrated in Figure 3.24.

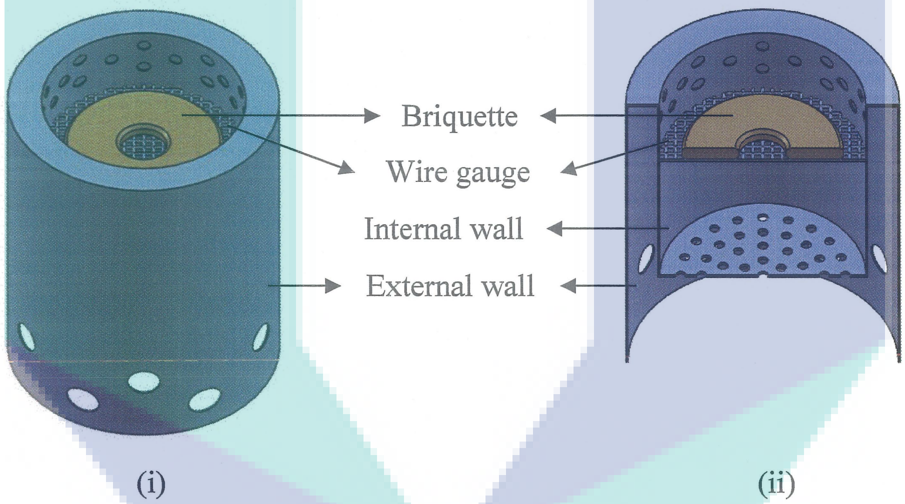


Figure 3.24 Biomass stove in (i) isometric view and (ii) sectional view

The apparatus required for this experiment included a Bunsen burner with lighter (ignition), stainless steel cup with lid (water container), thermometer with probe (temperature measurement), tripod stand, an adjustable platform, stopwatch (timing purpose) and a slip joint plier (holder). About 100 ml of tap water was used in the experiment.

The briquette was positioned upright to enable air flow from the bottom of the stove to the combustion area, and thus enhancing the burning efficiency. Meanwhile, the tripod stand was meant to prevent the direct contact between the stove and the base of the cup, and thus enabling the air flow from the gap during combustion. The experimental set up was displayed in Figure 3.25.

3.9.3.3 Burning rate

Burning rate was defined as the rate of solid fuel consumption when bringing water to a boil. It is calculated by dividing the equivalent fuel consumed by the time of the test as shown in the following equation.

$$Burning\ rate\ \left(\frac{g}{min}\right) = \frac{m_f}{t} \tag{3.9}$$

3.10 Correlation of briquetting parameters, mechanical and combustion properties

From the previous sections, the mechanical strength and combustion characteristics of the biomass briquettes produced from different feedstocks would be analysed. Nevertheless, the property enhancement of the briquettes, briquetting parameters and briquette burning could have interaction with one another. Meanwhile, the selected briquetting parameters could have influenced to the mechanical strength and the combustion characteristics of the final products. Further analyses were done to figure out the relationship between the variables involved.

In the first set of experiment, the effect of briquetting parameters (compacting pressure and preheating temperature) on the mechanical properties of the biomass briquettes produced from three residues individually. As reviewed in the previous chapters, pressure and temperature are the factors affecting the mechanical strength and durability of the densified biomass products. On top of that, the inherent nature of each biomass residue might vary each other, for instance the amount binding components within each biomass could be different. With the applied pressure and temperature during briquetting process, the materials are reduced in volume and strong bonds are created between particles to form a solid fuel. On top of that, lignin softens at the elevated temperature, also creates the inter-bonding and provides strength to the briquette's structure.

For the second set of experiment, the mechanical properties of the blend briquettes would be investigated with respect to the blend ratio. Mixing of different biomass materials could help to enhance the mechanical strength and durability, as proven in the previous research stated in Chapter 2. However, the optimum blend ratio for mixing of two different residues could be varied for each combination. For example, the addition of the materials with higher binding capability should be more for the two residues could complement each other and form a quality briquette with satisfactory strength. On the other hand, the combustion properties of the briquettes formed from three different combinations and four different blend ratios were investigated subsequently. As acknowledged, the calorific value, carbon, nitrogen, hydrogen and sulphur contents of the briquettes depend on the inherent nature of the biomass. Therefore, addition of different composition of the residues could affect the combustion performance of the final densified products. In addition, the burning rate, specific fuel consumption and power outputs of the bend briquettes were calculated from the results of water boiling test.

3.11 Summary

This chapter basically presented a comprehensive research methodology for the biomass briquettes formation and the relevant analyses for the mechanical properties and combustion characteristics investigation. Rice husk, sugarcane bagasse and spent coffee ground were chosen as the renewable sources in this research due to their significant benefits. Biomass briquettes without blending were first produced at two different manipulated briquetting parameters and their mechanical properties were studied accordingly. The optimum parameters were then selected for the subsequent biomass blends briquetting process.

The briquettes with two different residues were blended at mixing ratio, 20:80, 40:60, 60:40 and 80:20. After that, the effect mixing ratio on the mechanical properties of the blend briquettes including the pure residue briquettes was analysed. On top of that, the combustion properties of these briquettes were studied too. The results obtained from each of the experimental tests would be described in details in the next chapter.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Overview

In this chapter, the results of the experimental analyses described in the previous chapter would be presented. The mechanical strength, durability as well as the combustion characteristics of the biomass briquettes from three different feedstocks as well as the mixture of biomass residues was investigated respectively. The relationship between the manipulative variables to the mechanical properties as well as combustion characteristics of the briquettes were further analysed and discussed in the subsequent section.

4.2 Refinement on the briquette's structure

In this research, the objective of the study required a briquetting facility whereby the piston and mold set need to be designed and fabricated for the experimental purpose. Before the briquette could be produced, the structure or shape of the densified biomass needed to be determined.

As reported in Section 3.4.1, there were two different designs of the piston and mold set fabricated in the earlier stage of the research. The first type of briquette was taking the shape of hockey puck with the diameter of 50 mm with the reason stated in Section 3.4.1.1. The similar structure has been applied in several research. Figure 4.1 showed that the puck briquettes formed with spent coffee ground. The experimental testing thus had verified the feasibility of the designed briquetting facility.

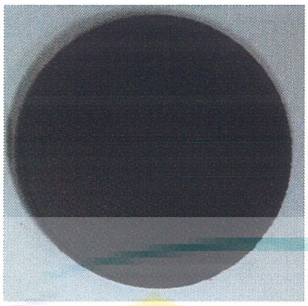


Figure 4.1 Puck briquette formed with spent coffee ground

As to improve the burning performance of the briquette, the second design of the densified product had been produced whereby a 15 mm middle hole was added, and thus forming briquettes illustrated in Figure 4.2. The briquettes formed were taking the shape of a doughnut. According to Yank and colleagues (2016), this particular briquette was believed to have more porosity and could be burnt more efficiently.

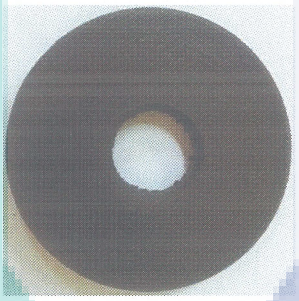


Figure 4.2 Doughnut-shaped briquette formed with spent coffee ground

In addition, a simple experiment was conducted to identify the water temperature change when two different briquettes were burnt to boil water. Both briquettes could be ignited within 1 minute with the aid of Bunsen burner, but differed in terms of water temperature to reach boiling point. As illustrated in Figure 4.3, the puck briquettes could only bring the water to boil at 92°C in 12 minutes and the briquette could not be burnt completely. On the other hand, the doughnut-shaped briquette could bring the boiling point of the water up to 100°C in 7 minutes and the briquette was completely burnt with white ashes left.

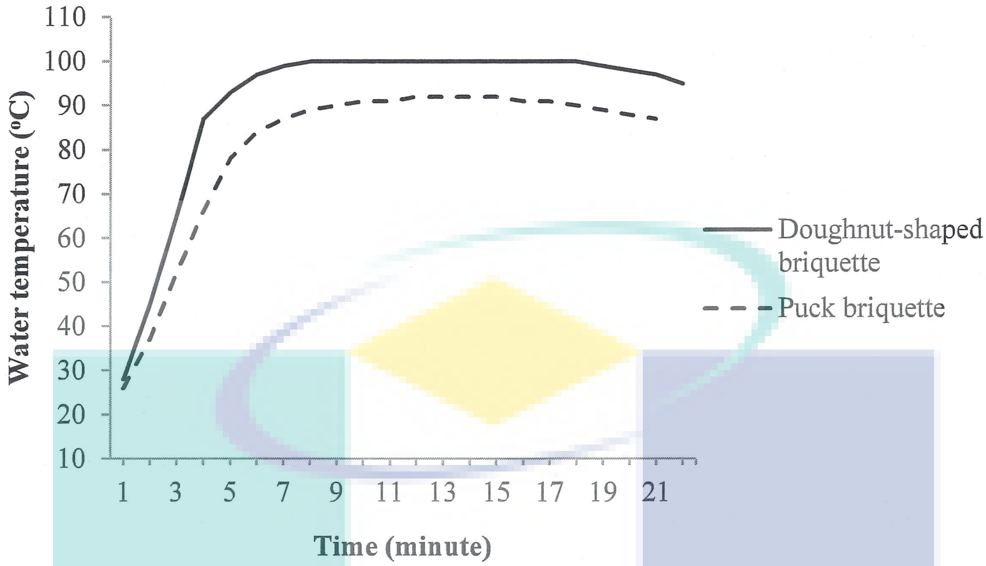


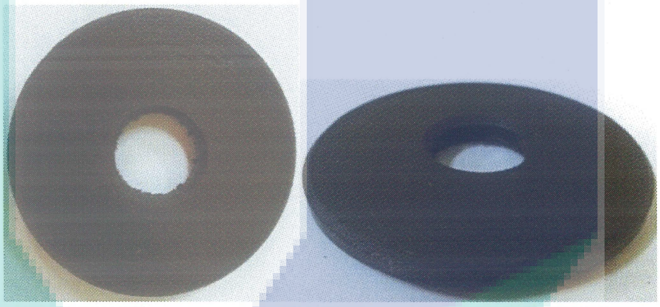
Figure 4.3 Water boiling temperature of two different briquettes

The result was consistent with the statement reported by Yank, Ngadi and Kok (2016), where the addition of a hole in the middle of the briquette could positively affect the burning performance by increasing the oxygen supply and porosity to enhance the combustion. With that lead, the second design, doughnut-shaped briquette was opted for this research study.

4.3 Production of biomass briquette

Once the design of the solid fuel was finalised, the biomass briquettes were formed with three different types of selected biomass feedstocks by using the custom-designed briquetting facility. The manipulating parameters involved the preheating temperature (120, 150 and 180°C) and compacting pressure (200, 250 and 300 bars), whereby the holding time was fixed at 30 seconds for every compaction. Thus, the average time taken for a briquette to be formed was around 10 minutes including the loading, waiting time for the temperature to rise, compacting, ejection and transferring to the workbench. The example of briquettes formed from the 150°C and 300 bars were listed in Table 4.1 according to the types of residues. A complete set of the briquettes with different level of variables could be viewed from Appendix C1-C3.

Table 4.1 Briquette formed from three different types of biomass feedstocks

Biomass residue	Briquette formed
Rice husk	
Sugarcane bagasse	
Spent coffee ground	

A total number of briquettes produced from different briquetting parameters were 27 units. Replicates were made for each analysis, meaning that a minimum of 81 briquettes were generated for each analysis, and thus around 400 briquettes had been produced in this research.

The positive outcomes could be seen in Table 4.1, where all the briquettes formed could sustain in a good shape. At the same time, the feasibility of the briquetting facility design for briquettes production was determined. A series of analyses was then conducted to identify the mechanical strength and the combustion characteristics of all the briquettes formed from the manipulative variables. The quality of the briquette needed to be taken care as the binding structure was crucial in term of handling, storage, transportation as well as combustion.

4.4 Mechanical properties analysis on the briquettes without blending

As highlighted in the literature, the process variables such as temperature and pressure could have influenced the quality of the densified products. Therefore, controlling the process variables is crucial as to produce quality biomass briquettes. In this section, the effect of the compacting pressure and preheating temperature on the mechanical properties of the biomass briquettes produced from three different residues would be analysed and discussed. The optimum briquetting parameters would be subsequently decided for the briquetting of biomass blends.

4.4.1 Shatter resistance

Table 4.2 lists down the average shatter resistance of the briquettes formed from the three types of biomass feedstocks.

Table 4.2 Average shatter resistance for the briquettes formed with single residue

Preheating temperature (°C)	Compacting pressure (bar)	Average shatter resistance (%)		
		Rice husk	Sugarcane bagasse	Spent coffee ground
120	200	72.42	99.93	82.02
	250	82.84	100.00	87.31
	300	90.08	99.97	89.12
150	200	78.86	99.97	84.09
	250	88.48	100.00	88.18
	300	96.43	100.00	90.14
180	200	95.67	99.97	90.61
	250	98.25	100.00	92.09
	300	98.65	100.00	89.63

Based on the recorded data shown in Table 4.2, the graphs were plotted accordingly as displayed in Figure 4.2 to Figure 4.4, where different biomass briquettes had achieved varying range of shatter resistance, which was expressed in percentage (%). The value of shatter resistance ranges from 0-100%, with 0% indicating total disintegration of the briquettes whereas 100% denotes no weight loss of the briquettes after the drop test.

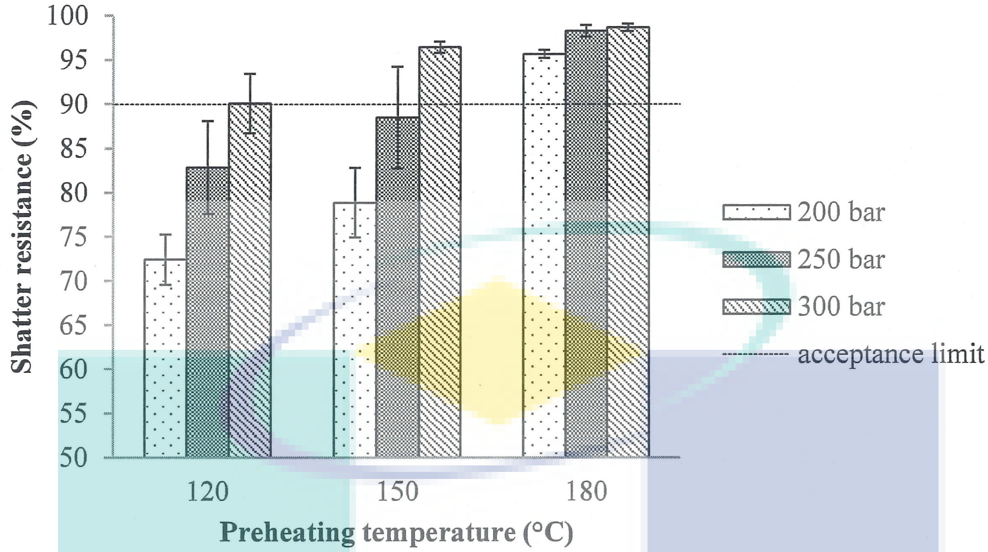


Figure 4.4 Effect of compacting pressure and preheating temperature on shatter resistance of rice husk briquettes

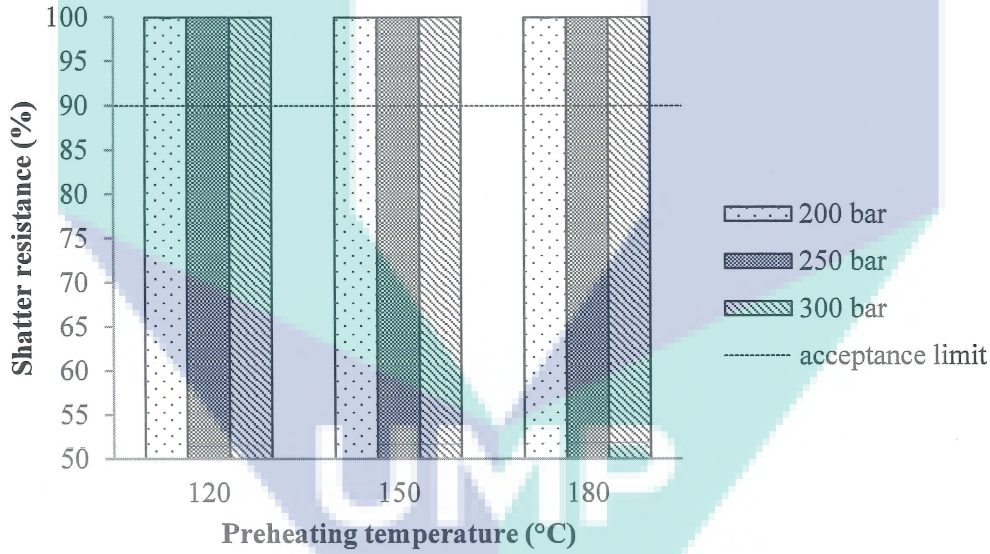


Figure 4.5 Effect of compacting pressure and preheating temperature on shatter resistance of sugarcane bagasse briquettes

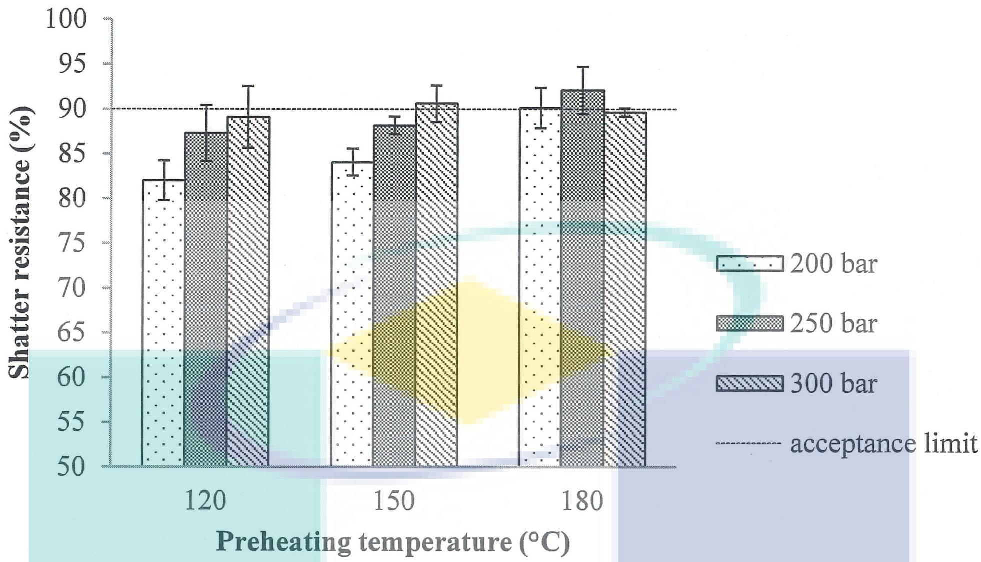


Figure 4.6 Effect of compacting pressure and preheating temperature on shatter resistance of spent coffee ground briquettes

Figure 4.4 shows that the shatter resistance of the rice husk briquettes compacted between the pressures of 200-300 bars at the temperature of 120-180°C. Higher shatter resistance implied a lower weight loss, contributing to high stability and resistance to handle stress. The results showed a positive trend whereby the shatter resistance of the rice husks briquettes increased gradually as the pressure and temperature were getting higher. A total 26.23% of increment in the briquettes' impact resistance was observed, implying that the outcome was in line with those stated in literature whereby the increase of compacting pressure and temperature might improve the briquette's strength.

At the same time, the graph as illustrated in Figure 4.4 also portrays the variations in shatter resistance as the temperature increased from 120-180°C at different compacting pressure. The shatter resistance of the briquettes produced at 200 bars increased from 72-95%. At 250 bars, the resistance to gravitational drop of the rice husk had risen from about 82-98%. Increasing the compacting pressure further to 300 bars, around 8% of additional increment was obtained as the temperature was increased from 120-180°C.

On the other hand, the shatter resistance of briquettes formed from sugarcane bagasse as displayed in Figure 4.5 was between 99.93% and 100%. It was found that the effect of increasing compacting pressure and the preheating temperature to improve shatter resistance of sugarcane bagasse briquettes was insignificant. Therefore, the briquetting pressure (200, 250 and 300 bars) and preheating temperature (120, 150 and 180°C) applied in this study were suitable to be used for the sugarcane bagasse densification with acceptable hardness.

For the case of the spent coffee ground briquettes, Figure 4.6 shows that the shatter resistance of these briquettes could be slightly improved with the elevated pressure and temperature. At 120°C and 150°C, briquettes formed from 200-300 bars resulted in an increase of 7.61% and 6.05% in the shatter resistance, respectively. At 180°C, however, fluctuation happened with 1.48% of increment from 200 to 250 bars and followed by 2.46% of decrement at 300 bars. Briquettes formed with 250 bars showed the highest shatter resistance (92.09%). Also, similar fluctuating trend could be found at 300 bars, whereby the briquettes produced at 150°C achieved higher shatter resistance (90.14%). This could merely explain that increasing the preheating temperature and compacting pressure would not necessary improve the hardness of the spent coffee ground briquettes.

According to the solid fuel standard mentioned by Borowski (2009), the shatter resistance of the solid fuel should be higher than 90%. Thus, this acceptance limit for shatter resistance was referred and the threshold lines had been plotted in each graph as shown from Figure 4.4 to Figure 4.6. For the briquettes made from sugarcane bagasse, all the briquettes had achieved the shatter resistance above 90%. On the contrary, a few of rice husk and spent coffee ground briquettes were within the acceptance range. By comparing the shatter resistance of the briquettes, the hardness of the briquettes could be ranked as follows: sugarcane bagasse > rice husk > spent coffee ground whereby sugarcane bagasse briquettes are highly durable to gravitational deterioration.

In this particular analysis, the briquettes made from sugarcane bagasse were experimentally proven to have better strength or hardness than the rice husk and coffee briquettes. This could be due to its fibrous structure and high lignin or natural binder contents within the particles. With the presence of these elements, the solid bridges, mechanical inter-locking bonds as well as adhesion forces between the adjacent particles could form right after the compaction especially under elevated temperature and pressure. Therefore, the sugarcane bagasse briquettes could sustain in a good shape after falling freely from 1 m high to the concrete floor for 10 times. The captured images of the briquettes before and after the drop test were listed in Appendix D2, according to the compacting pressure and preheating temperature.

On the other hand, some of the rice husks briquettes cracked and could not sustain in shape after the drop test. This could be caused by the absence of proper cross-linkage between some of the larger particles. As seen from Appendix D1, the condition did improve gradually and the briquettes did not disintegrate after encountering impact as the preheating temperature rose. The results were in line with the obtained data as portrayed in Figure 4.4, whereby those briquettes sustained in shape were exceeding the acceptance limit at 90%. It was proven that higher temperature was favoured for the rice husk densification to enhance the particles binding and strength of end products for none of additional binder was included for briquetting. The findings were supported by the research of Ahiduzzaman and Islam (2013) whereby higher temperature of 250-300°C was employed in the rice husk briquettes production using a screw extruder. Heating the rice husk up to this temperature range would soften the lignin and thus local bridges were formed due to the increase of the area of inter-particle contact. Another method used to promote the stronger binding would be through the addition of binders (Efomah and Gbabo, 2015), and the corresponding compacting pressure would be lower in the absence of heating process.

In the case of the spent coffee ground briquettes, the experimental outcomes showed that these solid fuels were quite fragile as all the briquettes disintegrated into few segments (Appendix D3) after the 10 continuous drops. Only 3 briquettes produced with different briquetting parameters were above the acceptance limit (90%). The hardness of the spent coffee ground briquettes was observed to have slightly lower as compared to the rice husk briquettes due to its lower lignin content, as listed in Table 2.2 and Table 2.5. Literature had highlighted that lignin was one of the main binding materials which could help to strengthen the inter-particle bonding of the briquettes, particularly when heat was applied. Due to the absence of fibrous structure within the spent coffee ground, the binding mechanism such as solid bridge and mechanical interlocking might be absent. Apparently, the inter-particles binding were considerably weak in the briquettes made from spent coffee ground and therefore the briquettes disintegrated in the drop test. The strength of these briquettes might be supported by the available hemicellulose, cellulose as well as the oil content, acting as the lubricants for binding enhancement. Besides that, there was a slight effect on the strength of these briquettes when pressure and temperature increased.

4.4.2 Abrasive resistance

The experimental results obtained from the tumbling test was tabulated according to the briquetting parameters (compacting pressure and preheating temperature) and types of biomass residues as shown in Table 4.3.

Table 4.3 Average abrasive resistance for the briquettes formed with single residue

Preheating temperature (°C)	Compacting pressure (bar)	Average abrasive resistance (%)		
		Rice husk	Sugarcane bagasse	Spent coffee ground
120	200	83.25	100.00	90.15
	250	85.98	100.00	95.45
	300	94.58	100.00	93.76
150	200	90.82	100.00	99.75
	250	96.10	100.00	99.79
	300	97.18	100.00	99.79
180	200	99.74	100.00	99.54
	250	99.71	100.00	97.52
	300	99.45	100.00	99.67

The graphs reflected the data recorded in Table 4.3 were plotted accordingly as displayed in Figure 4.7 to Figure 4.9. The abrasive resistance of the briquettes was calculated by using equations 3.5 and 3.6 where the outcome was expressed in percentage (%). The maximum value is 100 %, indicating no fines production and the briquettes remain intact after the test. However, briquettes with 0% of abrasive resistance will not sustain in shape and remain as fines or flakes.

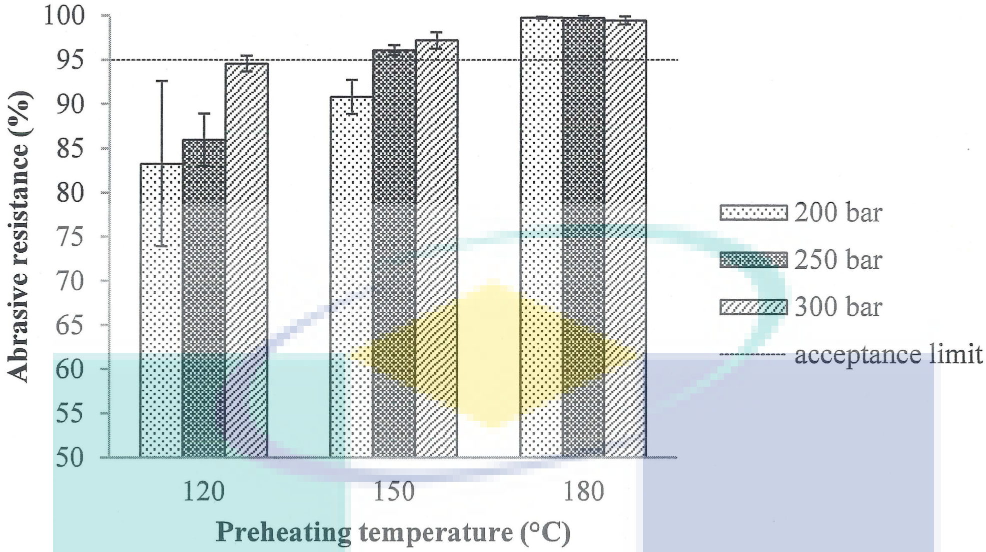


Figure 4.7 Effect of compacting pressure and preheating temperature on abrasive resistance of rice husk briquettes

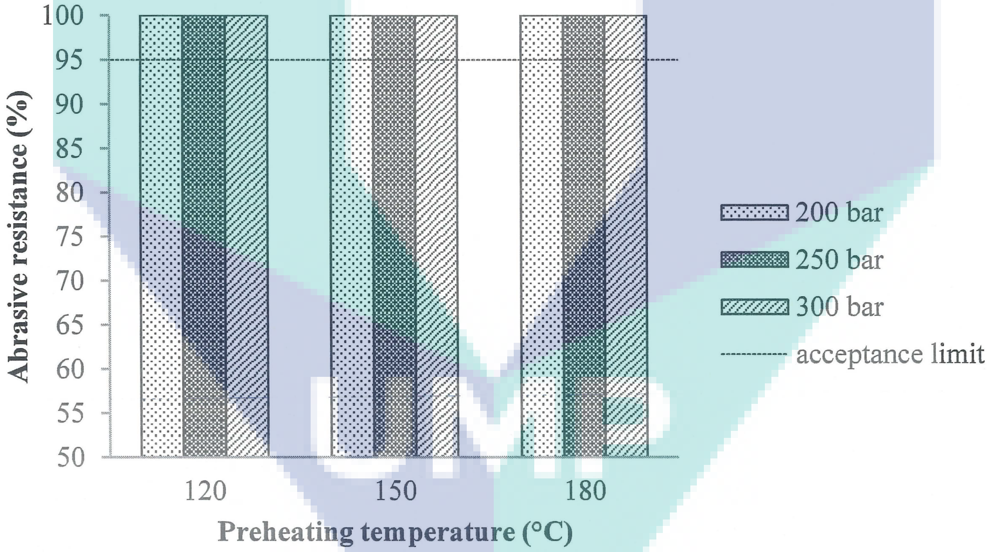


Figure 4.8 Effect of compacting pressure and preheating temperature on abrasive resistance of sugarcane bagasse briquettes

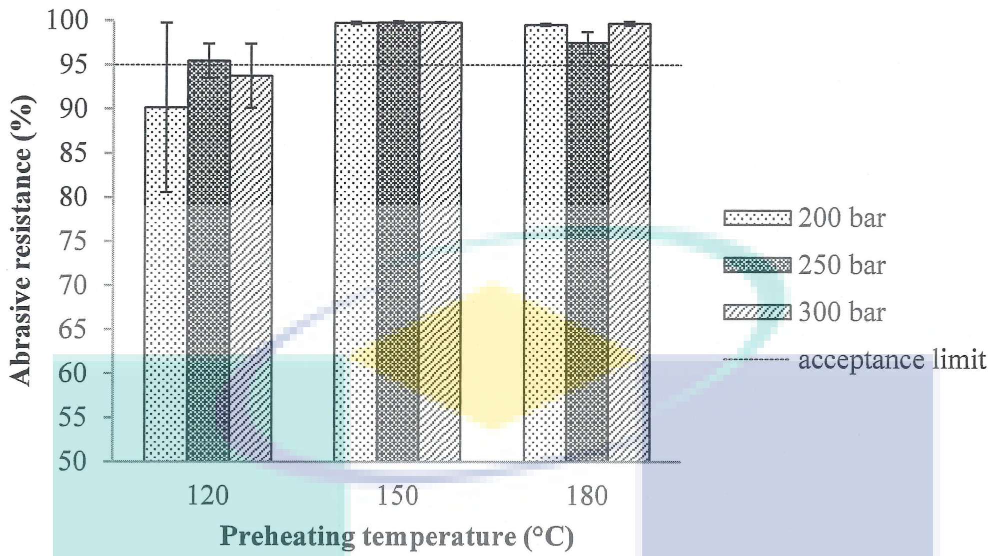


Figure 4.9 Effect of compacting pressure and preheating temperature on abrasive resistance of spent coffee ground briquettes

The abrasive resistance or durability of the briquettes densified with the pressures between 200 bars and 300 bars at the temperatures of 120, 150 and 180°C was presented in Figure 4.7, Figure 4.8 and Figure 4.9 for three different feedstocks. According to Missagia et al. (2011), abrasion was defined as the loss of particulate material due to handling of densified products, especially transportation in vehicle where vibrations might occur. Stronger and more durable briquettes produced lesser fines during handling, transporting and storing. Therefore, there was also an acceptance limit for the fines production, fines particles was mentioned not more than 5% in the review article of Kaliyan and Morey (2009). With that, the acceptance limit used in this study for abrasive resistance was set as ≥95% (plotted with dotted lines in each graph).

Figure 4.5 described the trend of abrasive resistance of the briquettes produced from rice husk. The manipulated preheating temperature apparently did possess impact on the durability of the rice husk briquettes. As the preheating temperature rose from 120 to 180°C, the abrasive resistance of the densified rice husk increased accordingly at three different pressures. On the contrary, the manipulated compacting pressure from 200 bars to 300 bars only improved the durability of the briquettes produced at 120°C and 150°C. For the briquettes produced at 180°C, there is no or insignificant influence of the pressures to the abrasive resistance, only with 0.03-0.26% of deviation. The highest value (99.74%) was recorded in the briquettes produced at 180°C and 200 bars whereas the rice husk briquettes formed at 120°C and 200 bars had the lowest value (83.25%) in abrasive resistance.

The fines percentage reduced gradually as the preheating temperature and compacting pressure increased, denoting a good sign with respect to the durability of the rice husk briquettes. The fines left would result in the ash production and consequently causing the cloggage of boiler or gasifier or stove. The rice husk particles on the surface of the briquettes did not stay intact and thus easily got peeled off when they encountered vibration. Based on a case study reviewed by Kaliyan and colleague (2009), researcher found that the durability of a similar briquette produced with 31.2 MPa (312 bars) was 95%. The result obtained in this study was almost similar to the research done previously.

On the contrary, Figure 4.8 depicts that a 100% of abrasive resistance was recorded for all the sugarcane bagasse briquettes produced at different compacting pressure and temperature. Apparently, the effect of the increased compacting pressure and preheating temperature applied during the densification process was insignificant to the durability of the sugarcane bagasse briquettes. There was a similarity in the results of abrasive resistance and shatter resistance of these briquettes and hence there could be a linear relationship between its strength and durability. Meanwhile, the durability of sugarcane bagasse briquettes produced in this experiment could meet the acceptance limit of 95%, as stated by Kaliyan and Morey (2009).

The briquettes remain intact after tumbling at 25 rpm for 5 minutes and no fines production. The availability of natural binding components (lignin, cellulose, hemicellulose, protein, etc) and fibrous structure of the sugarcane bagasse could contribute to the durability of the briquettes. As the briquettes were produced by elevated temperature, the natural binders especially lignin would soften and subsequently activate its binding functionality. Moreover, the powder-like sugarcane bagasse ground was fine enough and thus a larger surface area was created for particles bonding when pressure was applied (Kathuria and Grover, 2012).

As seen from Figure 4.7, there is a fluctuation on the abrasive resistance of the spent coffee ground briquettes. Surprisingly, the briquettes formed at 150°C achieved the highest abrasive resistance, 99.79% for 250 bars and 300 bars respectively. The results indicated that the increased of compacting pressure was not necessary for the spent coffee ground briquetting as the similar abrasive resistance could be obtained when the lower compacting pressure, 120°C was applied.

The images of the briquettes for the tumbling test were recorded and portrayed in Appendix E1-E3. The experimental outcomes showed that certain briquettes had the edges cracked. However, the briquettes produced at 150°C, from 200-300 bars remained in a good shape after the abrasion test. According to the acceptance limit of 95% in abrasive resistance, except the two briquettes produced at 120°C with the pressure of 200 and 300 bars, the other briquettes had fulfilled the specifications of the acceptance limit and can be categorised as the durable briquettes.

The results obtained in this analysis differed from the previous analysis (shatter resistance) for a minor impact was implied when the briquettes were subjected to tumbling in a dust-free container. It was also found that the briquettes produced from spent coffee ground was relatively low in strength when encountering impact; however they were good in shock resistance and more durable. In addition, it was observed that the durability of the spent coffee ground briquettes was better than rice husk briquettes. Although the amount of lignin within the coffee ground was lower, the coffee ground still could be compacted in a good shape when the pressure and temperature were applied during densification. Therefore, it was proven that spent coffee ground was having potential as raw materials for a quality briquette production.

4.4.3 Water resistance

The water resistance of the briquettes formed from rice husk, sugarcane bagasse and spent coffee ground at different level of variables was displayed in Table 4.4.The value recorded in this test is expressed in percentage (%), whereby 100% of water resistance represents no water gained after the test, while briquettes with 0% of water resistance will fully dissolve in water.

Table 4.4 Average water resistance for the briquettes formed with single residue

Pre-heating temperature (°C)	Compacting pressure (bar)	Average water resistance (%)		
		Rice husk	Sugarcane bagasse	Spent coffee ground
120	200	67.79	51.47	93.98
	250	65.38	54.13	93.91
	300	71.58	64.86	94.39
150	200	71.02	55.77	96.15
	250	69.35	63.05	95.52
	300	71.86	68.91	96.37
180	200	87.94	79.24	97.00
	250	87.03	86.04	97.17
	300	89.34	88.03	96.86

Based on the data recorded in Table 4.4, the graphs of water resistance versus preheating temperature and compacting pressure were plotted according to the type of biomass residue as portrayed from Figure 4.10 to Figure 4.12.

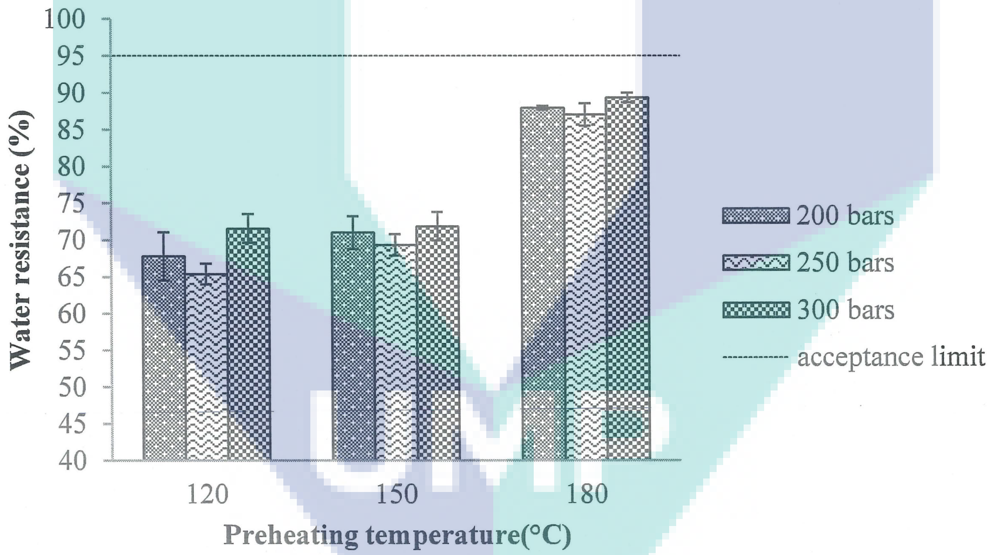


Figure 4.10 Effect of compacting pressure and preheating temperature on water resistance for rice husk briquettes

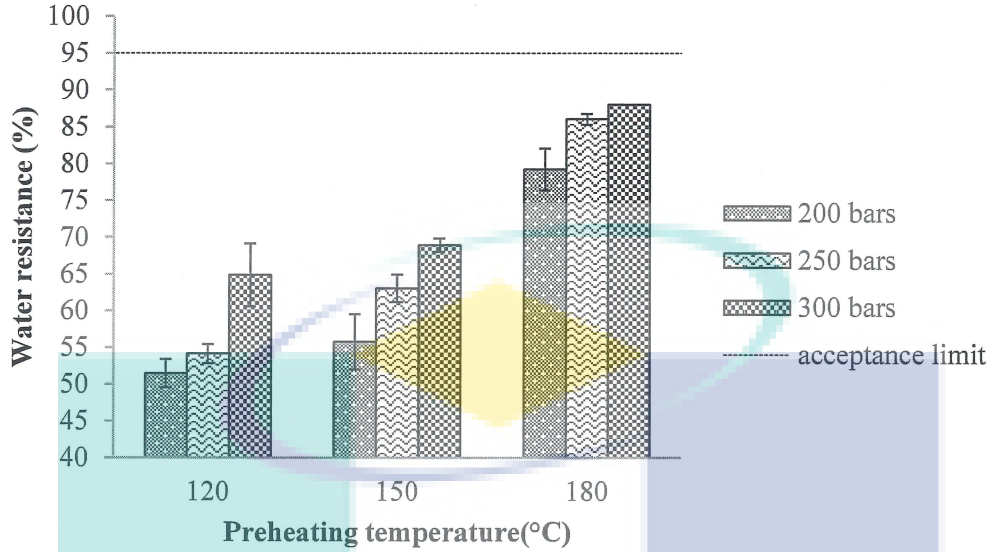


Figure 4.11 Effect of compacting pressure and preheating temperature on water resistance of sugarcane bagasse briquettes

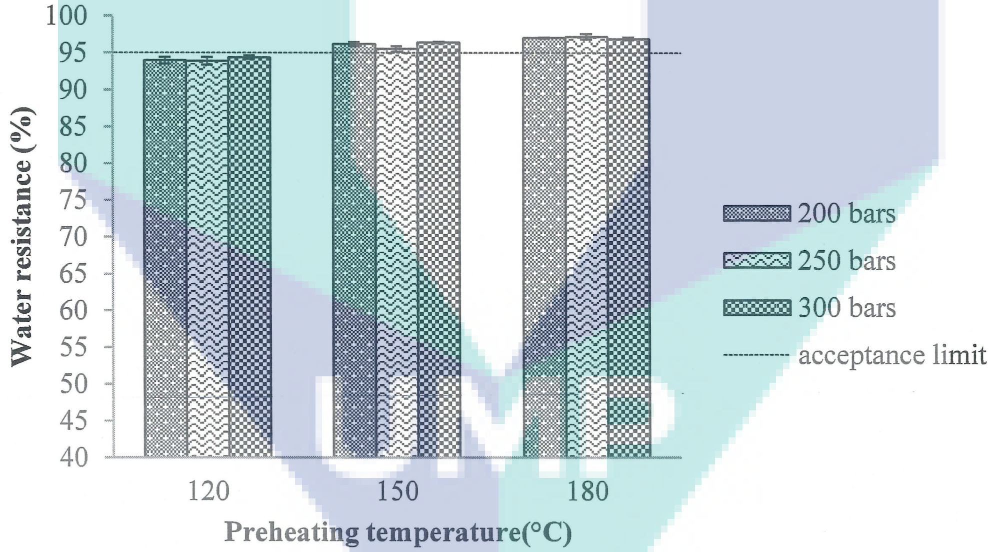


Figure 4.12 Effect of compacting pressure and preheating temperature on water resistance of spent coffee ground briquettes

As illustrated in Figure 4.10, the average water resistance of rice husk briquettes ranged from 67.9-89.34%. The graph obviously depicted that the water resistance of all the rice husk briquettes were below the acceptance limit at 95% which was in accordance to the review done Kaliyan and Morey (2009). Nevertheless, the experimental results showed that the increasing of compacting pressure and preheating temperature had effectively improved the water resistance of the rice husk briquette, either significant or insignificant. The densified rice husks produced at 120 and 150°C were having almost similar water resistance, with 4.07% of deviation. The preheating temperature seemed having more effect on the performance of these briquettes. The resistance to water absorption improved when the rice husk was heated up to 180°C. The water resistance of these samples rose to 87.94% at 200 bars and the highest water resistance (89.34%) could be seen in the briquettes produced at 300 bars.

Appendix F1-F3 displayed the images of the briquettes, showing their condition before and after immersing into the water. It could be seen that the rice husk briquettes expanded or swelled almost two-fold of the original size. Besides, the briquettes dispersed and could not be held anymore after about 2 minutes extracting from the water. This was attributed to the porous nature of rice husks and there might be gaps or void spaces existed between the particles, creating an opportunity for water penetration. This particular weakness could be resolved by using higher preheating temperature or adding binders during rice husks briquetting or addition of binders, which had been explained in the previous section.

On the other hand, the trend of the sugarcane bagasse briquettes with respect to the water resistance totally deviated from the previous analyses. In the last two analyses, there was insignificant effect of the briquetting parameters to the shatter resistance and abrasive resistance of the briquettes. However, the effect of the manipulating briquetting parameters could be seen in the water resistance test. According to the graph plotted in Figure 4.11, the increasing pressure and temperature had contributed to the enhancement of briquettes' water resistance.

At 120°C, 51.47-64.86% of the water resistance was recorded for the sugarcane bagasse briquettes compacted from 200 bars to 300 bars, at the interval of 2.66% and 10.73% of increment. The performance of these briquettes had been improved by increasing the temperature to 150°C whereby the recorded values from 200-300 bars were from 55.77-68.91%, slightly higher than the results obtained at 120°C. The water resistance of the briquettes continued to rise when the sugarcane bagasse was compacted at 180°C. At 200 bars, the results of water resistance had risen 23.47%, while 22.99% and 19.12% of enhancement were noted in the briquettes formed at 250 bars and 300 bars respectively.

Unfortunately, although the water resistance of the briquettes made from sugarcane bagasse increased with the elevated compacting pressure and preheating temperature, it was found that none of the briquettes was above the acceptance limit (95%). The briquettes produced from sugarcane bagasse were experimentally proven to be weaker in resisting water absorption due to its hydrophilic property. In addition, sugarcane bagasse was claimed to have a high absorption properties and thus used for many application as its cellulose fibres were pre-treated and used as reinforcing filler in high density polyethylene composites (Mulinari et al., 2010). Also, the comminuted sugarcane bagasse was fine enough and softer, which could promote water absorption. As mentioned previously, higher lignin contents were found in sugarcane bagasse and thus it could help in binding to produce higher strength and durability solid fuel. Mixing with materials with higher water resistance could be one of the alternatives to overcome this weakness of sugarcane bagasse and thus it could be efficiently used for energy production.

Interestingly, the briquettes made from spent coffee ground were observed to have higher water resistance as compared to that of rice husk and sugarcane bagasse. The water resistance of spent coffee ground briquettes ranged from 93.98-97.17%. The value difference between each briquette was not really significant. From Figure 4.12, the briquettes produced at 150 and 180°C for 200-300 bars were able to exceed the acceptance limit of the water resistance. However, with 0.61-1.09% of deviation, the briquettes formed at 120°C would able to achieve the acceptance limit. The manipulated pressure and temperature insignificantly affect the water resistance of the spent coffee ground briquettes.

The result obtained from immersion test was almost in line with the durability of the briquettes formed from spent coffee ground. The water resistance of the spent coffee ground briquettes was considerably higher than that of the rice husks as well as sugarcane bagasse. Kondamudi, Mohapatra and Misra (2008) found that the spent coffee ground contained approximately 15% of oil content. Its hydrophobic properties might be due to the oil content, acting as its own binding properties as well as the protective layer/coating to prevent water absorption. The inter-particles bonding was not highly affected for the briquettes still could sustain in shape and without getting swollen after the immersion process. Although lignin and fibers were absent, the constituents such as cellulose, protein and sugar within the spent coffee ground could act as the binding agents and contribute to the crystallinity of the briquettes. As mentioned by Kaliyan and Morey (2010), hydrogen bonding could be formed by highly polar components such as cellulose, starch and protein. This particular bonding might not be easily destroyed by water, but destructive forces.

4.4.4 Compressive resistance

The compressive resistance, expressed in maximum compressive load (N) of the briquettes produced from three different types of biomass feedstocks are shown in Table 4.5.

Table 4.5 Average compressive resistance for the briquettes formed with single residue

Preheating temperature (°C)	Compacting pressure (bar)	Average compressive resistance (N)		
		Rice husk	Sugarcane bagasse	Spent coffee ground
120	200	77.43	584.84	44.38
	250	86.10	724.38	50.75
	300	93.37	811.99	48.10
150	200	90.29	783.70	87.31
	250	128.49	988.65	90.35
	300	155.03	1077.78	97.51
180	200	116.91	903.66	102.41
	250	167.99	984.70	107.89
	300	236.29	1002.80	151.39

A better interpretation could be viewed in Figure 4.13, Figure 4.14 and Figure 4.15, showing the compressive resistance of the briquettes with respect to the compacting pressure and preheating temperature.

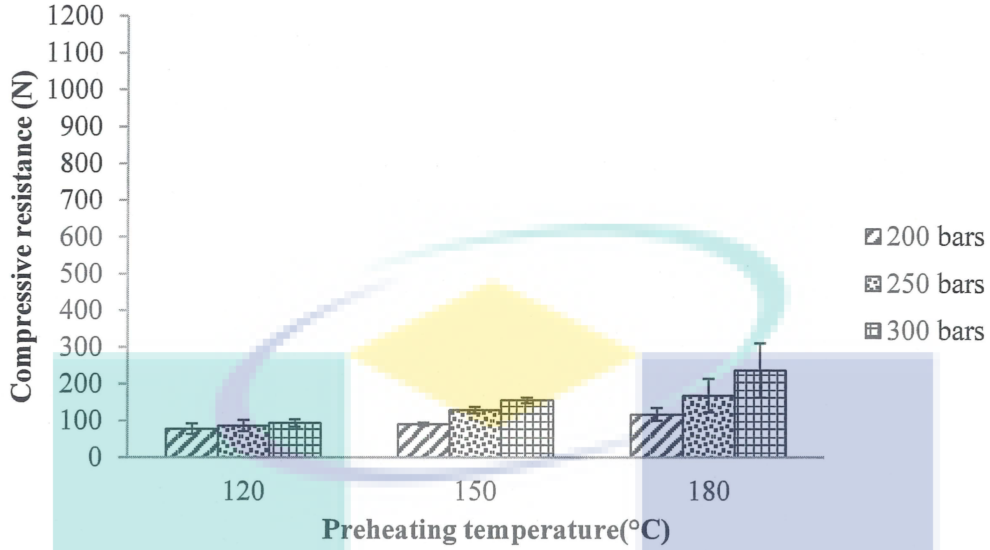


Figure 4.13 Effect of compacting pressure and preheating temperature on compressive resistance of rice husk briquettes

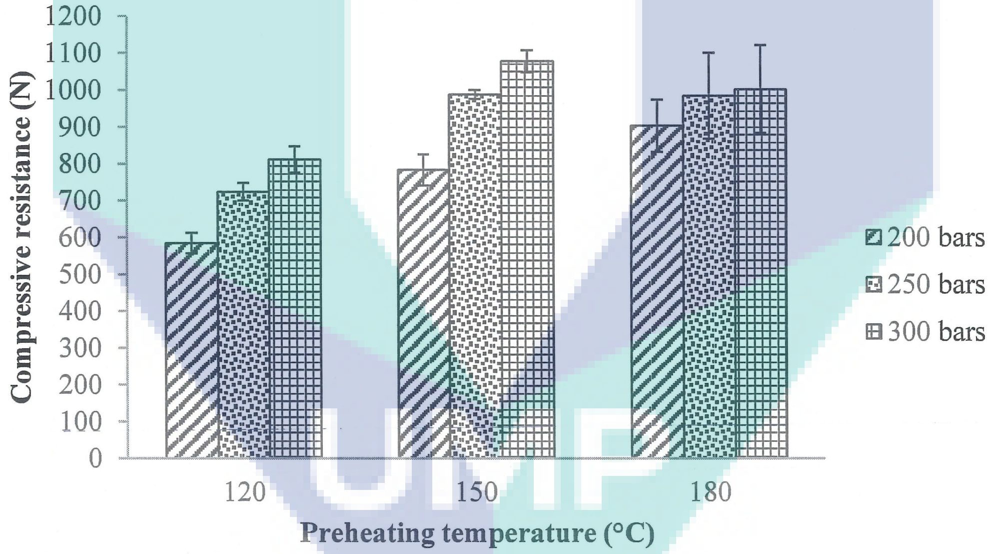


Figure 4.14 Effect of compacting pressure and preheating temperature on compressive resistance of sugarcane bagasse briquettes

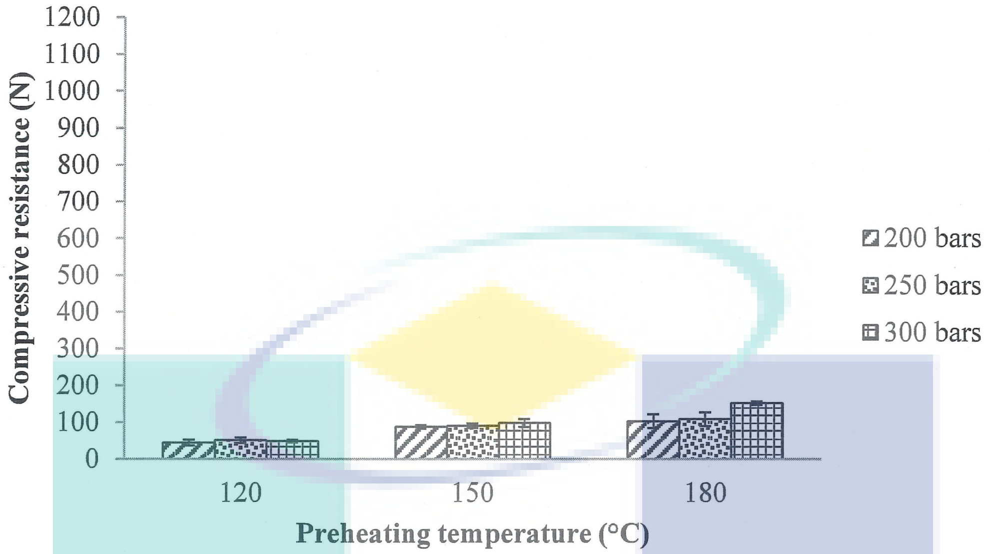


Figure 4.15 Effect of compacting pressure and preheating temperature on compressive resistance of spent coffee ground briquettes

Compressive resistance was used to measure the maximum crushing load that a briquette could withstand before cracking or breaking (Missagia et. al, 2011). Shuma and Madyira (2016) said that a good compressive strength and shatter index could help to promote the transportability of the biomass briquettes. This particular analysis could have a rough estimation of the internal strength of the briquettes. In other words, the maximum strength (N) supported by the briquette itself could be obtained through the compression test.

The mechanical strength of the briquettes was once again confirmed through the compression test, focusing more on their internal hardness. The compressive resistance was not measured in percentage; the maximum load at the break was obtained in N, directly from the compression machine. As mentioned by Kaliyan and Morey (2009), there is neither acceptance limit nor maximum value for the compressive resistance of the biomass briquettes.

The compressive resistance of the rice husk briquettes were ranging from 77.43 N to 236.29 N, as illustrated in Figure 4.13. The outcome from this analysis was in line with the shatter resistance and abrasive resistance, whereby the increasing temperature and pressure resulted in an increase of the resistance to shock, impact and compression. The maximum compressive strength of 236.29 N was achieved by the briquettes compacted at 300 bars and 180°C. The trend of the graph implied that there was possibility to increase the compressive strength of the briquettes when the temperature and pressure were raised.

In the case of sugarcane bagasse briquettes, their recorded compressive resistance values were higher, ranging from 584.84 N to 1077.78 N. As observed in Figure 4.14, the compressive resistance gradually increased with the increasing compacting pressure. However, increasing preheating temperature from 150 to 180°C possessed negative effect to the compressive resistance of the sugarcane bagasse briquettes, especially coupling with the pressure of 250 bars and 300 bars. The briquettes made from 150°C and 300 bars obtained the highest compressive resistance, indicating their internal strength is stronger due to the high binding capacity.

On the other hand, the compressive resistance of 44.38 N to 151.39 N was recorded in Figure 4.15 for the briquettes produced from spent coffee ground. As discussed in the previous sections, the strength of the spent coffee ground briquettes was relatively lower. As the temperature was raised from 120-180°C, the compressive strength of the briquettes increased when the pressure was fixed at 200 bars, 250 bars and 300 bars respectively. At the fixed temperature, on the other hand, the compressive resistance of the briquettes was improved with the increasing compacting pressure except the briquettes produced at 120°C. The internal strength of briquettes compacted at 250 bars were higher than that of 300 bars.

Based on the results obtained through the compression test, the trend of the internal strength of the briquettes could be arranged in this manner: sugarcane bagasse > rice husk > spent coffee ground, which is similar with the results recorded from shatter resistance and abrasive resistance tests. The internal strength of the briquettes was normally attributed to the materials nature, binding mechanism as well as the amount of binding materials, which had been discussed in the previous sections.

However, according to the review done by Kaliyan and Morey (2009), it was difficult for the compressive resistance test to prove a repeatability of the results for the same quality of densified products. This statement is in consistent with the results shown in this study, whereby the standard error for each bar actually deviated a lot although the briquettes produced with the similar briquetting parameters and undergo the similar analysis for three repetitions. There are researchers proving in their research that the compression resistance might not be a reliable measure of quality of the densified biomass products.

4.4.5 Summary on the mechanical properties of briquettes

From the analyses done in the previous sections, the effect of the manipulated pressure and temperature on the mechanical properties of the briquettes was investigated accordingly. In this study, it could be summarised that the hardness of the briquettes could be ranked as follows: sugarcane bagasse > rice husk > spent coffee ground. However, a descending trend was observed in the case of water resistance, in which the water resistance capability of the spent coffee ground briquette was among the best.

The deviation could be attributed to the variation of inherent properties for each feedstock as well as the amount of binding components within the materials. As reported by Missagia and partners (2011), different biomass materials might require different optimum conditions of densification. Increasing the briquetting pressure and temperature was thus proved to increase the shatter resistance, abrasive resistance, water resistance and compressive resistance of the briquettes. The optimum briquetting parameters could be decided from the analyses for the subsequent experimental study.

4.5 Optimum briquetting parameters

Based on the analyses done on the mechanical strength and durability of the briquettes made from pure residue, the optimal briquetting parameters could be selected. In accordance to the standard of the solid fuel, the strength and durability of the briquettes in terms of shear, abrasive and impact exceed the acceptance limits could be categorised as the quality solid fuel and subsequently could be burnt to generate heat and energy. Literature mentioned that the quality of the densified products could be influenced by several factors, including the briquetting parameters adopted in this study.

There were four different analyses used to investigate the strength and durability of the briquettes formed from three respective residues. According to the acceptance limit fixed in this research, the briquettes with the shatter resistance of 90% and above are considered good, whereas the briquettes that achieved 90% of abrasive resistance as well as the water resistance are categorised as a quality solid fuel which were beneficial for handling. Based on the analyses done in Section 4.4, 150°C and 300 bars were chosen and fixed as the briquetting parameters for biomass blends densification for most of the briquettes produced at 150°C and 300 bars had just passed the acceptance limit of mechanical strength and durability. The values obtained from the analyses were listed in Table 4.6 with the acceptance limit.

Table 4.6 Summary of mechanical properties of the briquettes produced at 300 bars and 150°C

Mechanical Properties	Rice husk	Sugarcane bagasse	Spent Coffee ground	Acceptance limit
Shatter resistance (%)	96.43	100.00	90.14	90.00
Abrasive resistance (%)	97.18	100.00	99.79	95.00
Water resistance (%)	71.86	68.91	96.37	95.00
Compressive resistance (N)	155.03	1077.78	97.51	-

Higher temperature was not desired in this study as the denaturation temperature of the binding components within the selected residues might vary. As mentioned in section 2.7.4, the briquette would become unstable and lower in strength when the temperature was increased, and thus causing it to burn for a shorter time. Also, higher preheating temperatures may lead to the occurrence of highly volatile elements or the feedstocks to burn. This condition happened in the briquettes made from sugarcane bagasse at 180°C, there was colour change on the sugarcane bagasse, indicating the residues were partially burnt. On top of that, some of the briquettes separated into two layers when extracting from the mold, some of the residues even deposited to the wall of the piston and mold. This indicated that the particles structure might be destroyed with higher temperature.

4.6 Biomass briquette formation from biomass blend

In this research, mixing of two different types of biomass residues was done between the three selected biomass residues, and therefore three combinations were formed. The first combination would be rice husk and sugarcane bagasse, followed by rice husk and spent coffee ground and lastly would be sugarcane bagasse and spent coffee ground. As observed with naked eyes, good shaped briquettes were achieved from different combinations and mixing ratio. Table 4.7 to Table 4.9 list out the briquettes formed with different blends ratio. There were a total of 12 briquettes produced from the blending of three different biomass residues.

Table 4.7 Briquettes produced from biomass blend - Part A

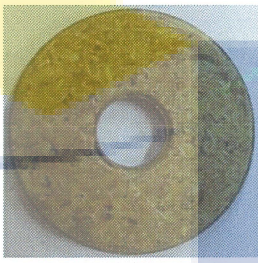
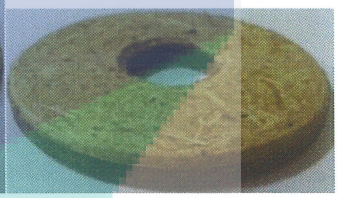
Biomass blend	Mixing ratio (wt.%)	Image
Rice husk : sugarcane bagasse	80 : 20	 
	60 : 40	 
	40 : 60	 
	20 : 80	 

Table 4.8 Briquettes produced from biomass blend - Part B

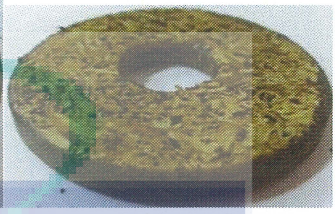
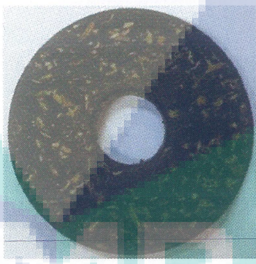
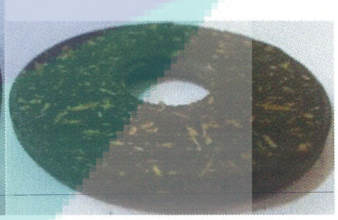
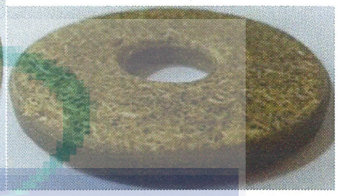
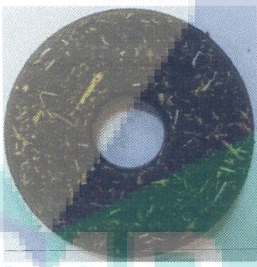
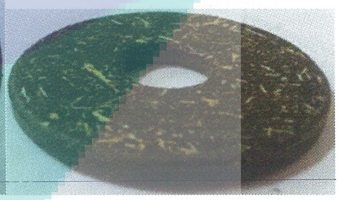
Biomass blend	Mixing ratio (wt.%)	Image	
Rice husk : spent coffee ground	80:20		
	60:40		
	40:60		
	20:80		

Table 4.9 Briquettes produced from biomass blend - Part C

Biomass blend	Mixing ratio (wt.%)	Image	
Sugarcane bagasse : spent coffee ground	80:20		
	60:40		
	40:60		
	20:80		

4.7 Briquette with mixture of rice husk and sugarcane bagasse

4.7.1 Mechanical properties analysis

Table 4.10 displayed the data obtained from the mechanical properties analysis of the briquettes formed with rice husk and sugarcane bagasse according to the mixing ratio (wt.%).

Table 4.10 Mechanical properties of the briquettes formed with rice husk and sugarcane bagasse

Rice husk: sugarcane bagasse (wt.%)	Shatter resistance (%)	Water resistance (%)	Abrasive resistance (%)	Compressive resistance (N)
100:0	96.43	71.86	97.18	155.03
80:20	99.95	69.91	99.96	324.83
60:40	99.97	76.66	100.00	633.09
40:60	100.00	84.97	100.00	634.74
20:80	100.00	84.87	100.00	709.55
0:100	100.00	68.91	100.00	1077.78

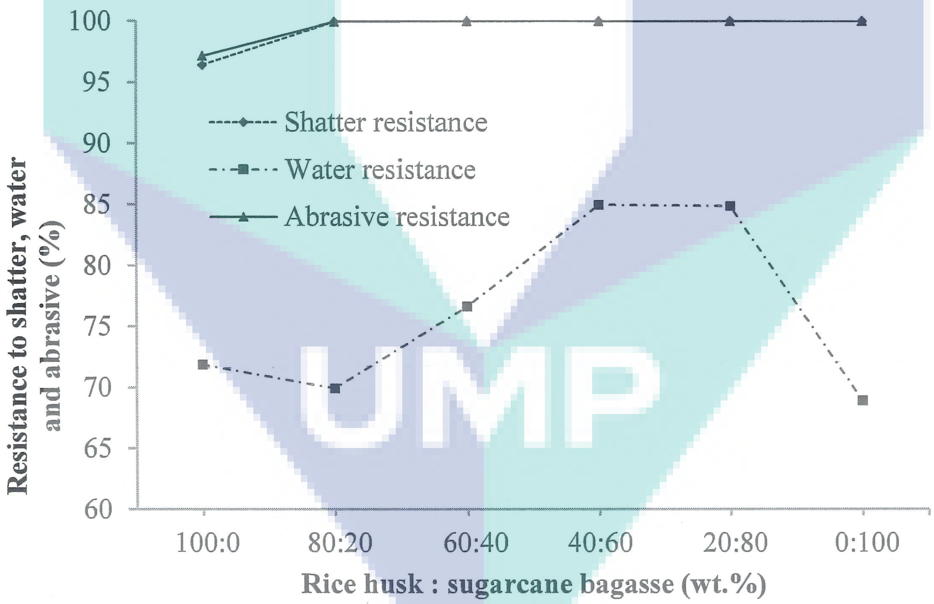


Figure 4.16 Effects of different blend ratio of rice husk and sugarcane bagasse to the mechanical properties

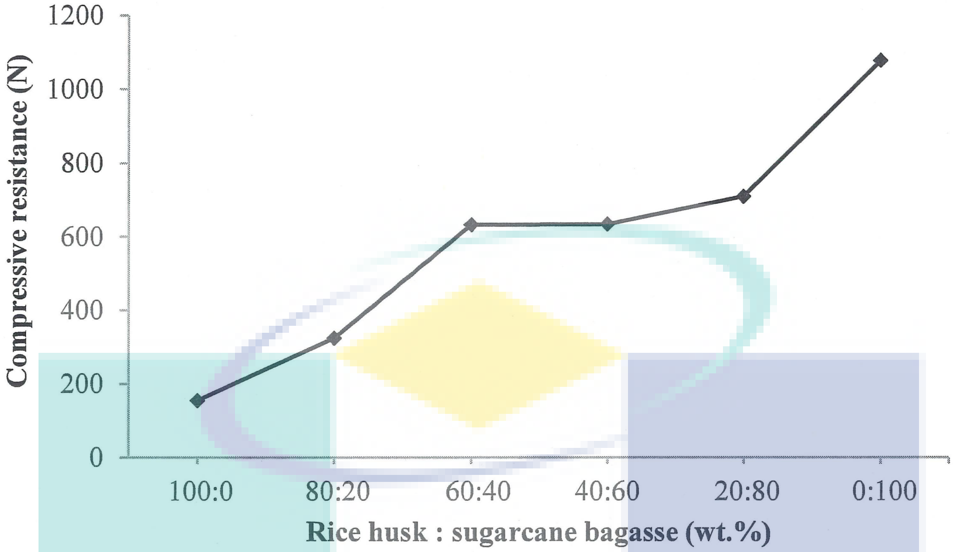


Figure 4.17 Compressive resistances for the rice husk and sugarcane bagasse with different mixing ratio

Figure 4.16 and Figure 4.17 depicted the mechanical properties of the briquettes with respect to different weight ratio of rice husk and sugarcane bagasse. Since the compressive resistance was measured in maximum load (N) and the other three analyses were measured in percentage (%), therefore two separated graphs were required to provide a clear view on the trend of the results obtained. The data reflecting the strength and durability of both pure rice husk and sugarcane bagasse briquettes were also illustrated in the figures, acting as the controls or reference. In the previous analyses, it was observed that the shatter resistance, abrasive resistance and compressive resistance of the sugarcane bagasse briquettes were higher than that of rice husk, however vice versa in the case of water absorption capability. Therefore, blending between rice husk and sugarcane bagasse was anticipated to improve the strength and durability of the briquettes.

As illustrated in Figure 4.16, the shatter resistance and abrasive resistance of the briquettes with different blends ratio portrayed a similar trend. By referring to the acceptance limit mentioned by Kaliyan and Morey (2009), briquettes from the blend of rice husk and sugarcane bagasse were all fulfilling the specifications for their shatter resistance and abrasive resistance fall within the acceptance limit range. It was also observed that the impact resistance and abrasive resistance increased with higher weight percentage of sugarcane bagasse, although the deviation was insignificant.

Moreover, the internal strength of these briquettes was recorded in terms of compression load (N) as illustrated in Figure 4.17. An ascending trend could be apparently viewed from the graph whereby the compressive resistance of these particular blends briquettes increased with the larger portion of sugarcane bagasse. From Figure 4.15 as well, it was shown that the compressive resistance of briquettes produced at 20:80 rice husks to sugarcane bagasse was twice that of the 100% rice husks. Besides that, the briquettes with 40 wt.% of sugarcane bagasse and 60 wt.% of rice husks shared the similar increment, almost twice of the previous weight ratio.

On the other hand, the water resistance property of these blends briquettes was apparently affected as displayed in Figure 4.16. A positive outcome was achieved when higher weight percentage of sugarcane bagasse was incorporated to form the briquette. The maximum water resistance (84.97%) was recorded in the briquettes formed in 40:60 of rice husk to sugarcane bagasse, with 13.11-16.06% of increment as compared to the pure residues briquettes. On the contrary, the briquettes with higher sugarcane bagasse compositions exhibited higher water absorption property, which was beyond the prediction. This might be due to its porous nature and gaps formed between adjacent particles and thus promoting water penetration.

An optical microscope with the magnification of 3x was adopted to observe the structure of the briquettes formed and the images were arranged accordingly in Figure 4.18. As shown in the Figure 4.18 (i) and (ii), the rice husk particles (red-circled region) were relatively larger, and thus gaps between the adjacent overlapped particles existed, resulting in the poor adhesion between adjacent particles and spring back effect. The addition of 40 wt.% sugarcane bagasse with rice husk had indeed improved the strength and durability of the briquettes, but there were still gaps as shown in Figure 4.18 (iii) which could still allow water penetration. As observed from Figure 4.18 (iv) and (v), a gradual improvement could be observed on the surface of the briquettes with 40:60 and 20:80 of rice husk to sugarcane bagasse, this could explain the improvement in the mechanical properties including the water resistance of the briquettes. Sugarcane bagasse particles could be squeezed into the gaps and voids of the biomass particles under high pressure, and subsequently protein denaturation and lignin softening acted as the binders at the elevated temperature. This could consequently result in the reduction of empty spaces between the adjacent particles, and thus creating a flatter and smoother surface.

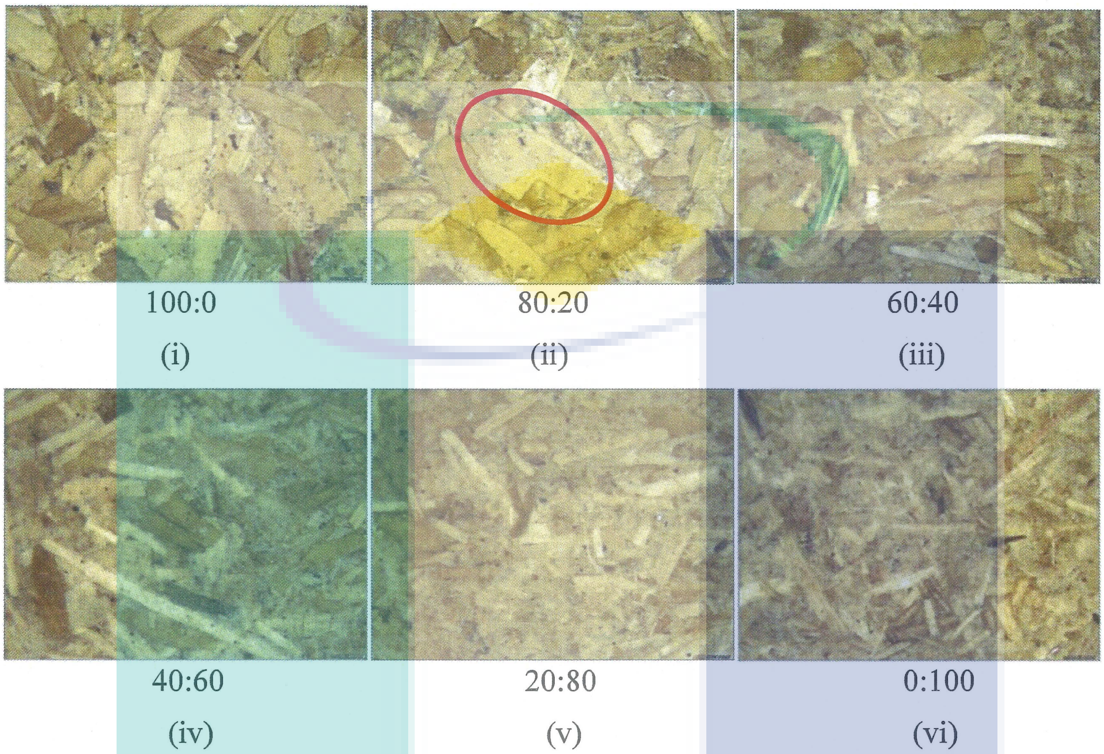


Figure 4.18 Microscopic images of the briquettes blends of rice husk to sugarcane bagasse

4.7.2 Combustion characteristics analysis of rice husk and sugarcane bagasse briquettes

The combustion performance of the briquettes formed with the combinations of rice husk and sugarcane bagasse was identified with respect to high heating value, Carbon (C), Hydrogen (H), Nitrogen (N), Sulphur (S) contents, thermal efficiency, power output, specific fuel consumption and burning rate. The graphs were plotted accordingly and displayed in Figure 4.19 to Figure 4.23.

4.7.2.1 High heating value of rice husk and sugarcane bagasse briquettes

Figure 4.19 illustrates the effect of different mixing ratio of rice husk and sugarcane bagasse to the high heating value or calorific value.

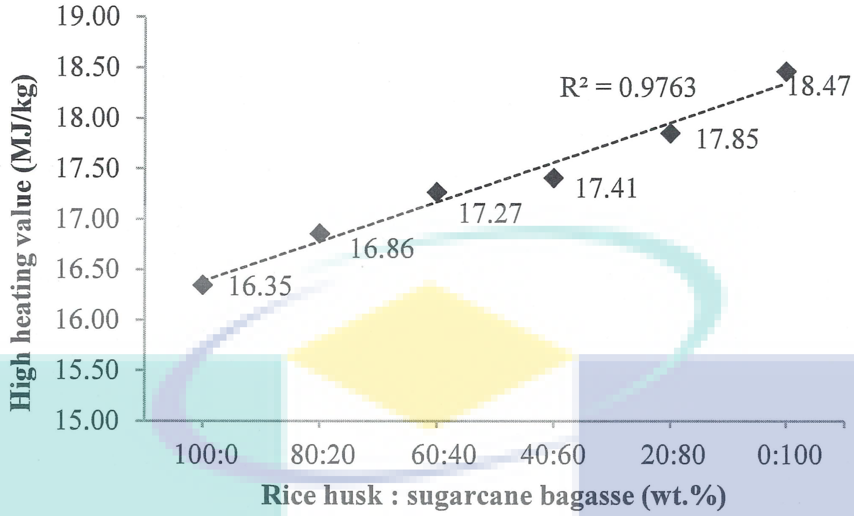


Figure 4.19 High heating value of rice husk and sugarcane bagasse at different blend ratio

Figure 4.19 illustrated the effect of different mixing ratio of rice husk and sugarcane bagasse to the high heating value or calorific value. The high heating value for rice husk and sugarcane bagasse briquettes are 16.35 MJ/kg and 18.47 MJ/kg respectively. The calorific value of the rice husks shown in Figure 4.19 appeared to be slightly higher than the literature value in Table 2.2 since heat was applied during densification, which might affect the value. While the obtained value for sugarcane bagasse was within the range listed in Table 2.3.

As stated in DIN 51731, the minimum requirement of calorific value for a commercial briquette must be higher than 17500 J/kg or 17.5 MJ/kg (Faizal, Latiff, Wahid and Darus, 2009). As a comparison, it was found that the rice husk briquettes did not fulfil the minimum requirement whereas sugarcane bagasse briquettes did. Despite being that, Efomah and Gbabo (2015) reported that this energy value of rice husk was sufficient enough to generate heat for household cooking and small scale industrial applications. Therefore, rice husk was anticipated to have potential as a solid fuel if combined with other material which might help in boosting up the energy value. In the first set of experiment, sugarcane bagasse was chosen to be blended with rice husk.

Mixing of these two residues was experimentally proven to improve the high heating value of the briquettes gradually. The graph shown in Figure 4.19 portrayed a strong positive correlation ($R^2 = 0.9763$), denoting that the increasing weight ratio of sugarcane bagasse could increase the high heating value of the briquettes formed. When the mixing ratio 40:60 of rice husk to sugarcane bagasse, the high heating value of the briquettes approach nearly to 17.5 MJ/kg and subsequently exceeded this value when the mixing ratio became 20:80. This was an indication that the calorific value was mostly influenced by the composition of sugarcane bagasse which was higher in heating value.

4.7.2.2 Ultimate analysis of rice husk and sugarcane bagasse briquettes

A biomass was claimed to contain larger compositions of carbon, hydrogen and oxygen whereas a small portion of Nitrogen and Sulphur (Jittabut, 2015). These elements compositions would affect the briquettes' combustion characteristics. The obtained values in this experiment as displayed in Figure 4.20 were in line with the literature statement, whereby the carbon and hydrogen contents were higher than that of nitrogen and sulphur.

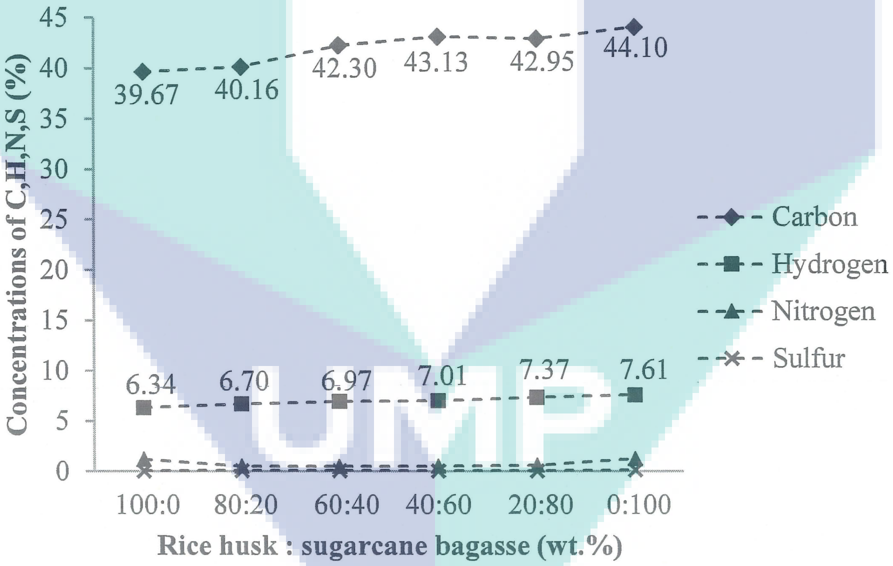


Figure 4.20 Ultimate analysis of rice husk to sugarcane bagasse with different mixing ratio

In the briquettes formed with different mixing ratio of rice husk and sugarcane bagasse, it was found that the carbon content lied within the range of 39.67 to 44.10% whereas 6.34-7.61% of Nitrogen was detected in these briquettes. With the increased of sugarcane bagasse weight ratio within the briquettes, a gradual increment on the Carbon and Nitrogen contents was detected in this solid fuel. On the other hand, the compositions of Nitrogen and Sulphur within this blend briquette were relatively uniform for different mixing ratio and the recorded values were smaller as compared to that of the foregoing elements. From Figure 4.20, there was insignificant change on the sulphur contents (0.06-0.12%) although the briquettes were produced at different mixing ratio. An agreement could be observed when the value obtained in this experiment was compared to the literature value in Table 2.2, whereby the sulphur content of rice husk was found to be within the range of 0.08-0.61%.

On the other hand, it was observed that 100 wt.% rice husk briquettes and sugarcane bagasse briquettes contained 1.19% and 1.26% of Nitrogen as demonstrated in Figure 4.20. In comparison of the results obtained in this work with those reviewed in Table 2.1 and Table 2.3, the former obtained a value slightly higher than the literature (0.1-0.8%) whereas the latter achieved a lower value as compared to the previous research of Yin (2016). This variation might be due to the utilization different source or species of the similar biomass residues in the research. Nevertheless, when the rice husk was mixed with sugarcane bagasse to form the briquettes, the Nitrogen compositions decreased to less than 1% which was desirable as mentioned by Jittabut (2015). This could be an indication on the success of this particular materials mixing whereby the harmful emissions could be reduced.

4.7.2.3 Results from water boiling test for rice husk and sugarcane bagasse briquettes

Besides determining the heating value and elemental compositions of the briquettes, the burning performance of the briquettes was investigated through water boiling test, which was one of the common methods. The possible results obtained from this particular experimental testing included power output, specific fuel consumption and lastly burning rate.

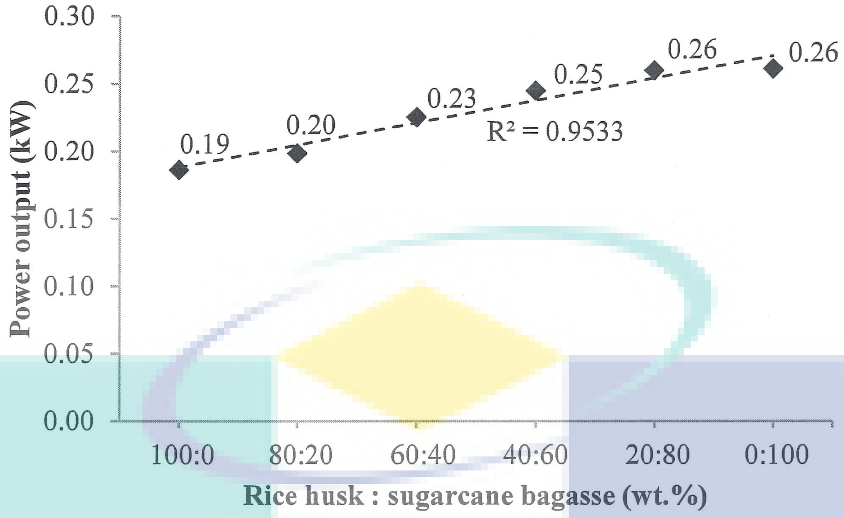


Figure 4.21 Power output for different mixing ratio of rice husk and sugarcane bagasse briquettes

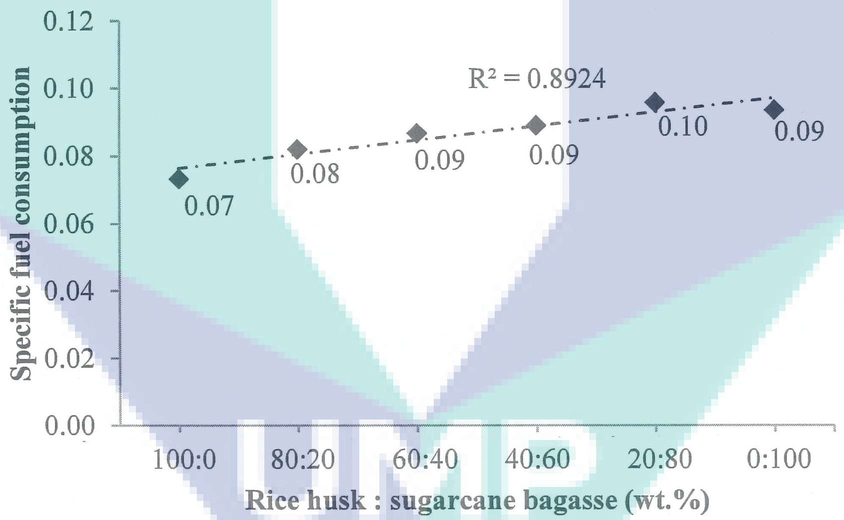


Figure 4.22 Specific fuel consumption of briquettes formed with rice husk and sugarcane bagasse at different mixing ratio

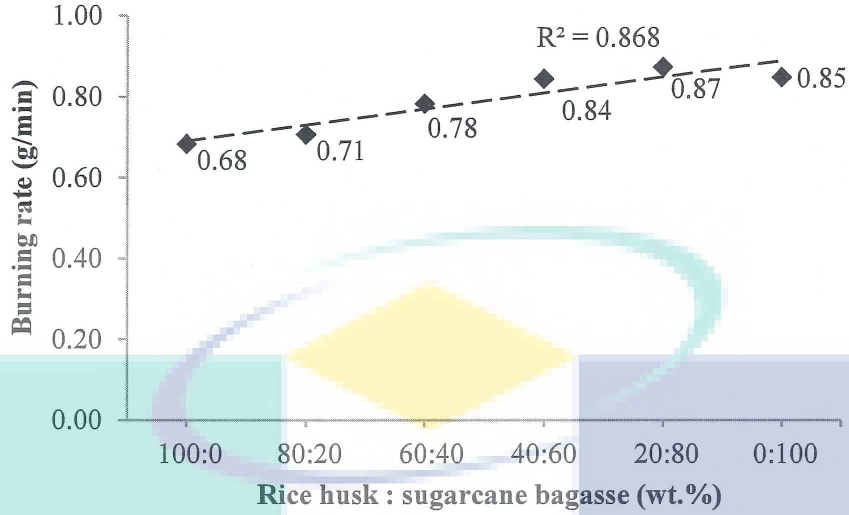


Figure 4.23 Burning rate of rice husk and sugarcane bagasse mixture at varying blend ratio

From the water boiling test, several results could be obtained and thus combustion characteristics of the briquettes formed could be identified particularly power output, specific fuel consumption as well as burning rate. These values for the briquettes formed from the combinations of rice husk and sugarcane bagasse had been recorded in Figure 4.21 to Figure 4.23. In this experiment, it was observed that the maximum boiling point could be achieved by using this blend briquette was around 98°C. The mechanical strength of these briquettes could be reaffirmed in this particular testing for the briquettes did not crumble easily while being ignited and these briquettes were burnt completely with lesser ashes left.

From Figure 4.21 to Figure 4.23, it was discovered that the obtained values of sugarcane bagasse briquettes were higher than that of rice husk briquettes. This could be the reason that sugarcane bagasse contained more volatile matter than rice husk. The findings from the past research of Efomah and Gbabo (2015) showed that the rice husk briquettes contained 68.20% of volatile matter whereas 81.50-83.66% of volatile matter was recorded in sugarcane bagasse according to those stated in literature (Table 2.3). Also, this could be due to higher calorific value of sugarcane bagasse briquettes as compared to the blend and rice husk briquettes.

Hence, increasing the weight ratio of sugarcane bagasse would definitely increase the power output, specific fuel consumption and the burning rate of the briquettes as well. In the case of power output, the lowest value was recorded in the pure rice husk briquettes, 0.19 kW. But with the incorporation of sugarcane bagasse, the values increased progressively to around 0.26 kW. A positive correlation ($R^2 = 0.9533$) was observed between the power output and the increased weight ratio of sugarcane bagasse.

A similar trend plot could be seen in Figure 4.22 and Figure 4.23 for the specific fuel consumption and burning rate. As stated by Rajaseenivasan and his team (2016), specific fuel consumption was the amount of fuel required to reach the boiling stage of 1 kg of water. The higher specific fuel consumption of the briquette, the lesser it will be required to boil the water efficiently. The values recorded in this blend were within the range of 0.07 to 0.10 kg of fuel/ kg of water while the highest values belonged to the briquette formed with the mixing ratio of 20:80 (rice husk-sugarcane bagasse).

According to Onuegbu et al. (2011), there are factors affecting the burning rate of the biomass for instance chemical composition and geometry (bulk, packing and orientation). It was discovered that the burning rate of the briquettes with blend of rice husk to sugarcane bagasse (0.87 g/min) in the mixing ratio of 20:80 was slightly higher than that of the pure sugarcane bagasse (0.85 g/min). It was undeniably the mechanical strength as well as the calorific value of the later was better than the former, but with the addition of rice husk, the briquette would be porous and thus allowed the oxygen infiltration and outflow of combustion products which subsequently resulted in higher burning rate.

4.8 Mixing of rice husk and spent coffee ground

The mechanical properties and combustion properties analysis of the mixture of rice husk and spent coffee ground were discussed in details in the following sections.

4.8.1 Mechanical properties analysis

The values obtained from mechanical strength tests of the briquettes with the blends of rice husk and spent coffee ground in different weight ratio were listed in Table 4.11 whereas the trends of the result were plotted in Figure 4.24 and Figure 4.25.

Table 4.11 Mechanical properties of the briquettes with blends of rice husk and spent coffee ground

Rice husk: spent coffee ground (wt.%)	Shatter resistance (%)	Water resistance (%)	Abrasive resistance (%)	Compressive resistance (N)
100:0	96.43	71.86	97.18	155.03
80:20	96.70	91.02	97.57	175.06
60:40	96.77	92.43	98.60	148.28
40:60	96.06	94.74	99.43	175.10
20:80	95.58	94.92	99.86	185.04
0:100	90.14	96.37	99.79	97.51

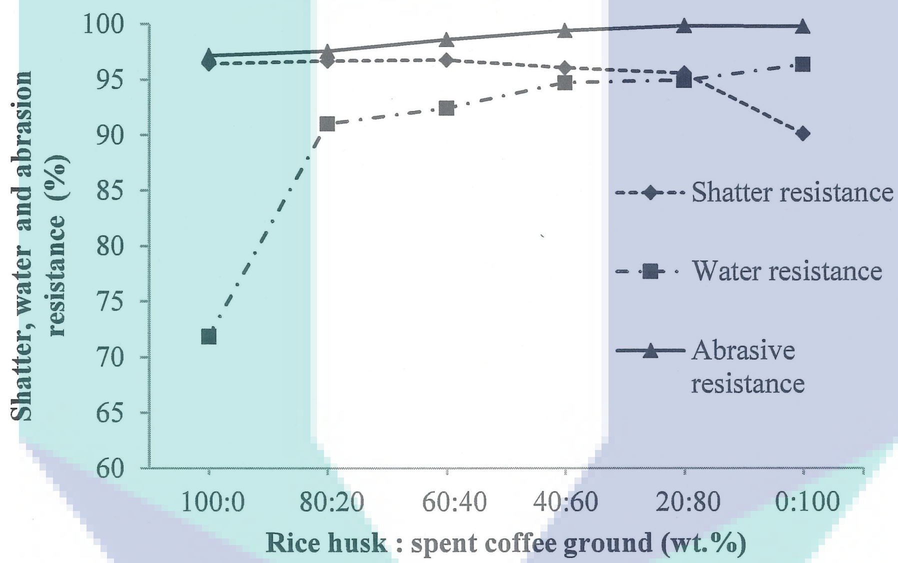


Figure 4.24 Effects of different blend ratio of rice husk and spent coffee ground to the mechanical properties

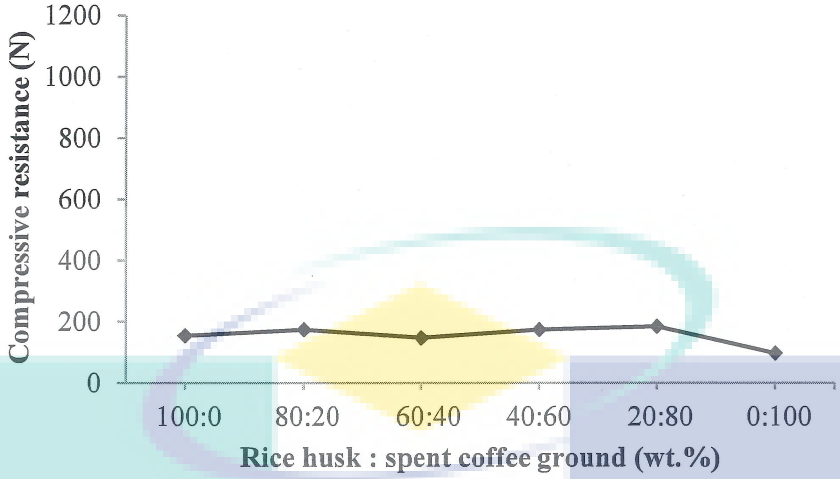


Figure 4.25 Compressive resistances for the rice husk and spent coffee ground with different mixing ratio

As for the second combination, sugarcane bagasse was replaced by spent coffee ground and blended with rice husk to form briquettes. In Figure 4.24 and Figure 4.25, the results of the pure residues briquettes were also plotted with the mixing ratio of 100:0 and 0:100 of rice husk to spent coffee ground as a benchmark or reference. It was observed that the shatter resistance and compressive resistance of rice husk briqeuttes were higher than spent coffee ground bagasse briquettes and vice versa in the case of water resistance and abrasive resistance. This indicated that there were strengths and weaknesses on these two residues.Therefore, it was anticipated to obtain a better quality of briquette by mixing of these residues at varying blend ratio.

A decreasing trend plot could be observed in the shatter resistance of the briquettes as portrayed in Figure 4.24. The highest shatter resistance was recorded in the briquettes with the mixing ratio of 60:40 (96.77%). Comparing the rice husk briqeuttes and the blend one, the changes on shatter resistance were insignificant, with only 0.07-1.19% of deviation. However, the shatter resistance of the spent coffee ground briquettes was 5.44–6.63% lower than the blend briquettes. Besides that, all the briquettes achieved the shatter resistance with ≥90% in which the minimum requirement of the acceptance limit was fulfilled.

From the same figure as well, it was shown that the abrasive resistance of the briquette ranged from 97.18-99.86%, with a gradual and insignificant increment when the spent coffee ground compositions raised. In the case of water resistance, the recorded value for spent coffee ground briquette was 24.51% more than the rice husk briquettes. Therefore, blending of spent coffee ground with rice husk was anticipated to enhance the water resistance of the densified products. As viewed from Figure 4.23, 19.16% of enhancement was achieved even when only 20 wt.% spent coffee ground was mixed with the rice husk and followed by a gradual increment (<4%) when 40 wt.%, 60 wt.% and 80 wt.% of spent coffee ground were added.

However, the internal strength was measured through the compression test whereby 185.04 N was the highest compression forces that the rice husk and spent coffee ground briquettes (20:80) could withstand. Similar to the shatter resistance, the compressive resistance of spent coffee ground briquette was lower than that of rice husk briquette. From these four different tests, it was discovered that the hardness of the briquettes degraded with the increased of spent coffe ground, however vice versa in the case of durability.

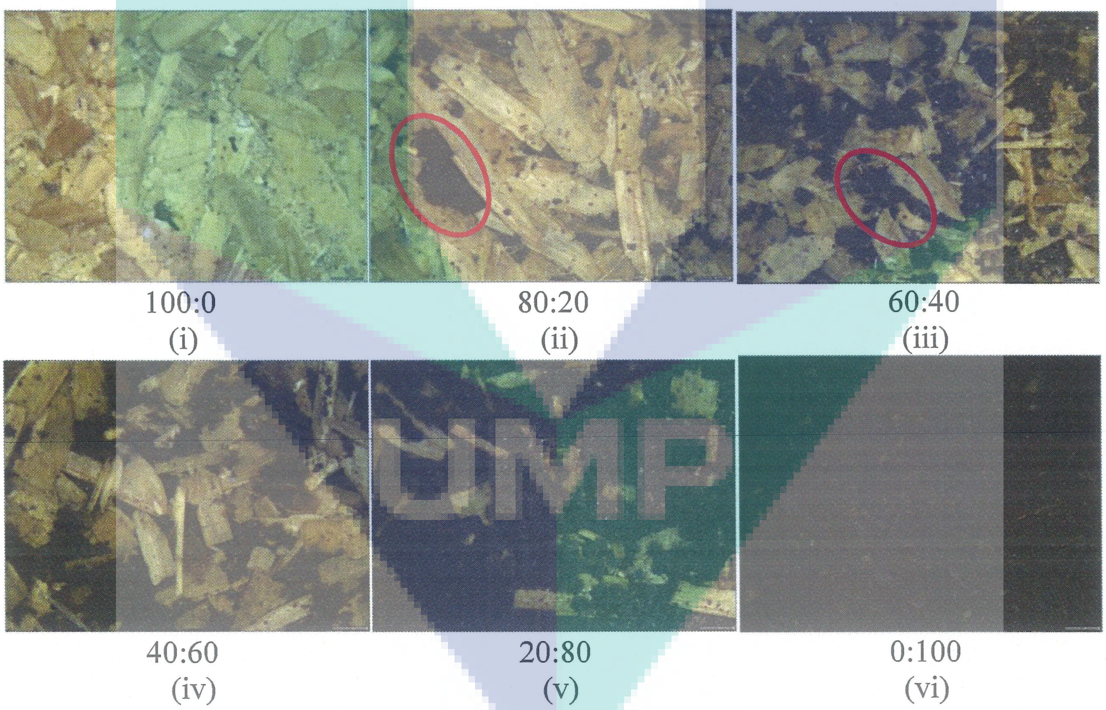


Figure 4.26 Microscopic images of rice husk to spent coffee ground briquettes at different mixing ratio

By taking the research of Stelte et.al (2010) as reference, the inter-particle gaps of briquettes as illustrated in Figure 4.26 (i), (ii), (iii) and (iv) were an indication of poor adhesion between adjacent particles and spring back effects, leading to weak inter-particle bonding of the briquettes. When 20 wt.% spent coffee ground was mixed with

80 wt.% of rice husks, the shatter resistance and abrasive resistance slightly increased for spent coffee ground was squeezed into the gaps of rice husk particles (red-circled region), reinforcing the structure of the briquette and providing it with a sustainable shape as shown in Figure 4.26 (ii) and (iii).

The rice husk particles observed under the optical microscope were relatively larger as compared to the spent coffee ground powder, coupled with its porous structure and thus offering a larger surface for the spent coffee ground to stick on it. It was apparently shown that these two residues did not diffuse together under the application of heat and pressure due to their different inherent characteristics.

4.8.2 Combustion properties analysis

High heating value, elemental compositions of the briquettes as well as the results obtained from water boing test resulted from different mixing ratio of rice husk to spent coffee ground were listed and discussed in the subsequent sections. On top of that, the graph plotted for each analysis would include the results of pure residue briquettes.

4.8.2.1 High heating value of rice husk and spent coffee ground briquettes

Figure 4.27 presented the trend plot of high heating value obtained in the briquettes with the blend of rice husk and spent coffee ground in different mixing ratio as well as the pure residue briquettes. High heating value or calorific value was an indication of the energy value of a fuel, a fuel without a certain energy value would be considered useless and thus more fuels were required for a certain amount of heat generation.

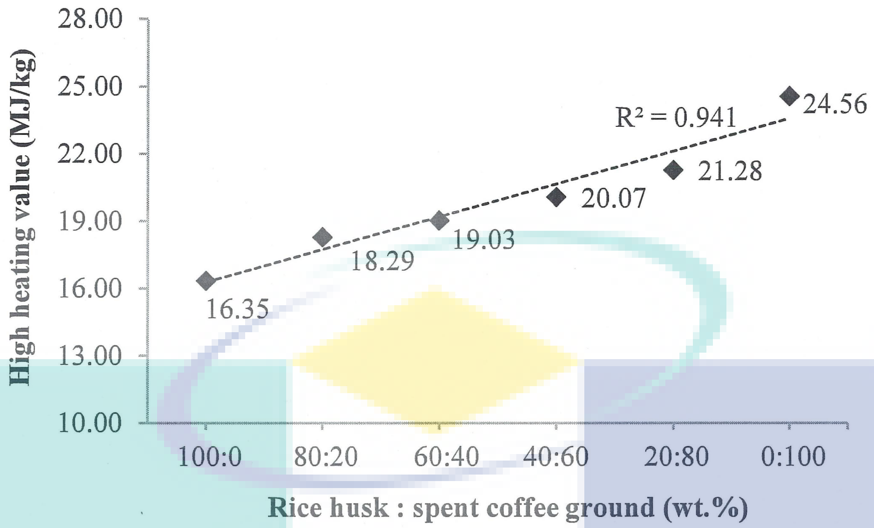


Figure 4.27 High heating value of briquettes with the combinations of rice husk and spent coffee ground

Spent coffee ground could be reutilised or recycled as the fuel in industrial boilers as well as biodiesel and fuel pellets due to its high calorific value (Mussatto et al., 2011). The bomb calorimeter gave a reading of 24.56 MJ/kg for the pure spent coffee ground briquettes. However, a lowest high heating value was recorded in the pure rice husk briquettes, 16.35 MJ/kg. The rice husk briquettes did not fulfil the minimum requirement stated in DIN 51731 as a commercial briquette, but briquettes formed with spent coffee ground did.

Therefore, mixing of these two different residues would be an interesting approach and it was observed that there was increment in the high heating value of the blend briquettes especially when more spent coffee ground was incorporated. The addition of 20, 40, 60 and 80 wt.% of spent coffee ground to the rice husk had resulted in the enhancement of caloric value from 16.35 to 21.28 MJ/kg as compared to the pure rice husk briquettes. Besides, the results reflected the positive outcome whereby a strong liner relationship was demonstrated with the R^2= 0.941, implying that the high heating value increased proportionally when every 20 wt.% of spent coffee ground were mixed with the rice husk.

A similar research conducted by Ciesielczuk, Karwaczyńska and Sporek (2015) added 10% and 25% of spent coffee ground to the beech wood and obtaining the calorific value of 19.12 MJ/kg and 20.32 MJ/kg respectively. In the similar research, the densified products were comparable to the poor quality hard coal whereby the calorific value of the hard coal was between 16.7 and 32.7 MJ/kg, whereas brown coal's calorific value ranged from 8.5-16.6 MJ/kg. The findings obtained in this study was thus in line with this particular research whereby the incorporation of spent coffee ground could improve the energy value of the solid fuel. On top of that, this could be an indication whereby these biomass briquettes especially with 20: 80 of rice husk to spent coffee ground could replace the use of coal (lignite) in heat and electricity generation since they had a similar energy value.

4.8.2.2 Ultimate analysis of rice husk and spent coffee ground briquettes

Figure 4.28 summarises the results of ultimate analysis for the briquettes with mixture of rice husk and spent coffee ground in different blend ratio.

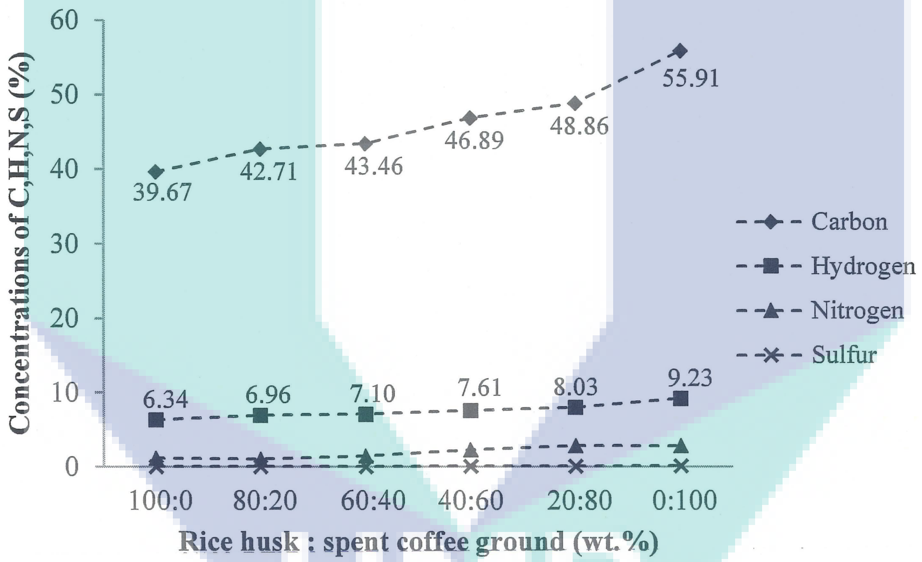


Figure 4.28 Ultimate analysis of rice husk and spent coffee ground blend briquettes at different mixing ratio

Forero-Nuñez, Jochum and Sierra (2015) mentioned that there was a close relationship between carbon, hydrogen content and the energy value (calorific value). This was because the oxidation of Carbon and Hydrogen would release more quantity of energy during combustion. In a simple meaning, the higher Carbon and Hydrogen content the briquettes had, the higher its energy content. From this study, it was significantly showed that the Carbon (55.91%) and Hydrogen (9.23%) content of spent coffee ground briquette were among the highest as compared to the values obtained for the blend as well as the pure rice husk briquettes. Therefore, the highest Carbon and Hydrogen content of the spent coffee ground could obtain highest calorific value.

On the other hand, Nitrogen and Sulphur concentrations within the densified biomass should be concerned due to their capability of forming pollutants such as Nitrogen Oxides (NO_x) and Sulphur Dioxides (SO_2), which might bring detrimental effects to the environment. Nevertheless, retaining low reaction temperature during combustion could control the Nitrogen oxidation; however sulphur reaction with air was more complicated to control (Forero-Nuñez, Jochum and Sierra, 2015). A valuable advantage of using biomass as fuel was because of its low Sulphur content. In this study, it was found that the pure rice husk briquettes and the blend one had less than 0.1% Sulphur. On top of that, the highest Sulphur content (0.13%) was recorded in the spent coffee ground briquettes whereas the lowest value (0.04%) belonged to 20:80 of rice husk to spent coffee ground.

4.8.2.3 Results from water boiling test for rice husk and spent coffee ground briquettes

Figure 4.28 to 4.30 demonstrated the results calculated from the parameters determined during the water boiling test. The specific fuel consumption, burning rate and power output were used to evaluate the combustion performance of the biomass briquettes produced in this study.

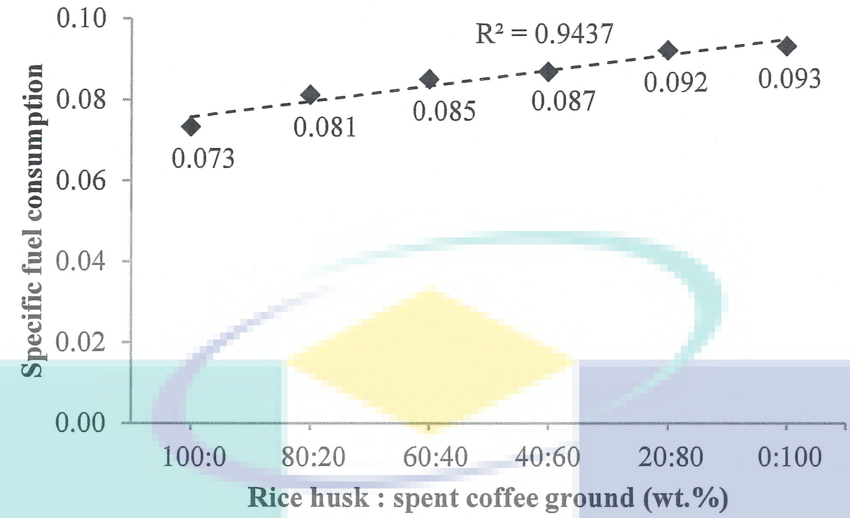


Figure 4.29 Effect of mixing ratio to specific fuel consumption of rice husk-spent coffee ground briquettes

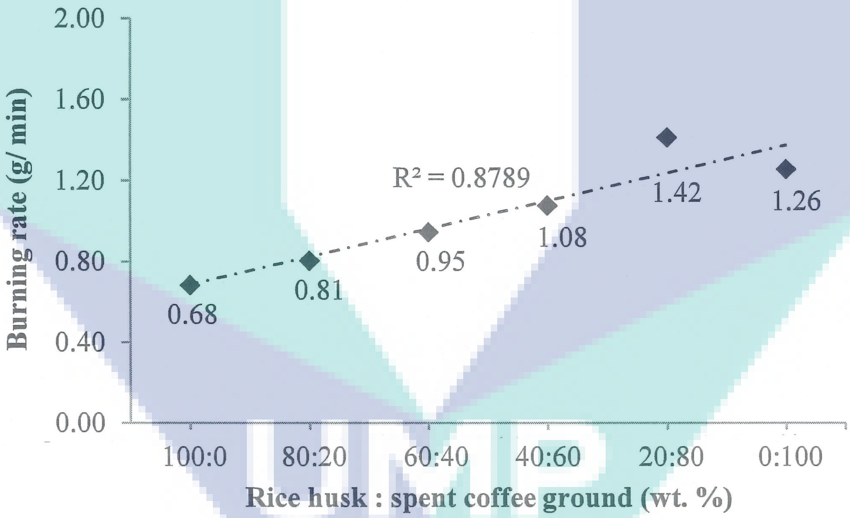


Figure 4.30 Burning rate of the briquette with different mixing ratio of rice husk to spent coffee ground

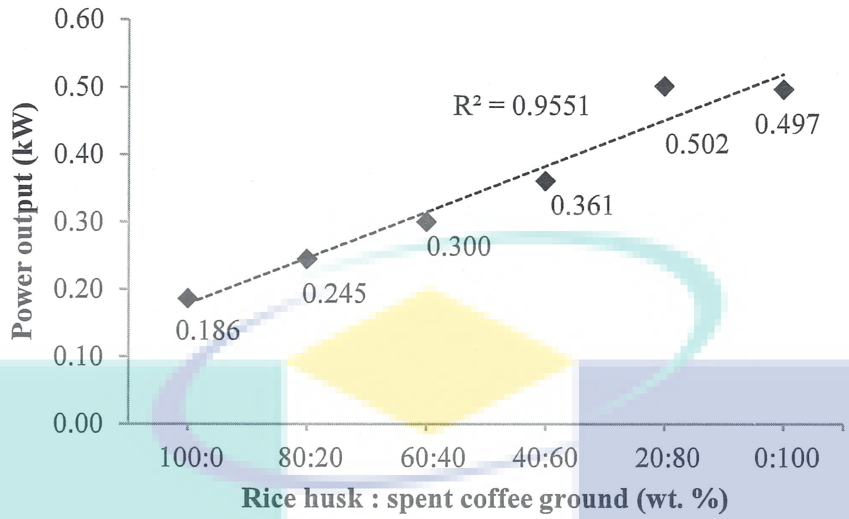


Figure 4.31 Effect of mixing ratio to power output of the briquette with rice husk and spent coffee ground

In this study, the calculated burning rate would determine how fast the fuel burnt, while specific fuel consumption measured the quantity of the fuel required to boil 1 kg of water; the lower it is, the more economical the briquette will be. Besides that, the power output or energy released from the fuel was obtained by multiplying the calorific value and burning rate. However, comparing the specific fuel consumption, burning rate and power outputs, it was observed that the cooking efficiency of the briquettes formed with more spent coffee ground concentration was higher.

Figure 4.29 showed that the specific fuel consumption of the briquettes ranged from 0.073 to 0.093 kg of fuel/ kg of water, with only 0.02 kg of fuel/ kg of water deviation between the highest and lowest values. The recorded specific fuel consumption increased progressively with the increase of spent coffee ground weight percentage of the briquette. The values obtained in this study were considered valid if compared with the findings done by Rajaseenivasan and his team (2016) whereby the specific fuel consumption for the blending of sawdust and neem powder ranged from 0.09 to 0.16 kg of fuel/ kg of water.

On the other and, the burning rate of the briquettes were between 0.68 g/min and 1.42 g/min. The briquettes produced from pure rice husk briquettes exhibited the lowest burning rate. There was an agreement between this study and the research done by Ooi and Siddiqui (2000): they found that the burning rate of densified rice husk was around 0.6 g/min when compacted at 10 bars. On top of that, during the ignition, rice husk flakes on the surface started to peel off and the maximum boiling temperature recorded by using one piece of rice husk briquette (~ 10 g) was around 88°C. This is because of the fact that the briquettes burnt slowly and thus the heat released was lost before water boiled which subsequently resulted into the lowest power output (0.186 kW).

However, the burning rate of the briquettes with more spent coffee ground increased gradually as shown in Figure 4.30. This could explain from the fact that the spent coffee ground had higher calorific value and also the oily components within it could help to increase the burning rate (Chin and Aris, 2013). From the water boiling test, it was observed that the briquettes formed with 40 wt.% of spent coffee ground or above were able to boil the water at 100°C.

Interestingly, the briquettes with 20:80 of rice husk to spent coffee ground obtained the highest burning rate (1.42 g/min), slightly higher than that of pure spent coffee ground briquettes. This was because the former took the shortest time (6 min) to bring the water to boil in comparison to the former (7.7 minutes). Therefore, this blend briquette (20:80) also had the highest power output (0.502 kW), which was influenced by its burning rate and calorific value.

4.9 Briquettes with mixture of sugarcane bagasse and spent coffee ground

4.9.1 Mechanical properties analysis

The mechanical properties of the briquettes made from the blends of sugarcane bagasse and spent coffee ground were listed accordingly in Table 4.12. The results included shatter resistance, water resistance, abrasive resistance as well as compressive resistance.

Table 4.12 Mechanical properties of the briquettes with blends of sugarcane bagasse and spent coffee ground

Blend ratio (sugarcane bagasse to spent coffee ground)	Shatter resistance (%)	Water resistance (%)	Abrasive resistance (%)	Compressive resistance (N)
100:0	100.00	68.91	100.00	1077.78
80:20	100.00	88.21	100.00	650.83
60:40	100.00	91.82	100.00	626.38
40:60	99.97	93.12	100.00	484.59
20:80	99.68	93.55	100.00	232.73
0:100	90.14	96.37	99.79	97.51

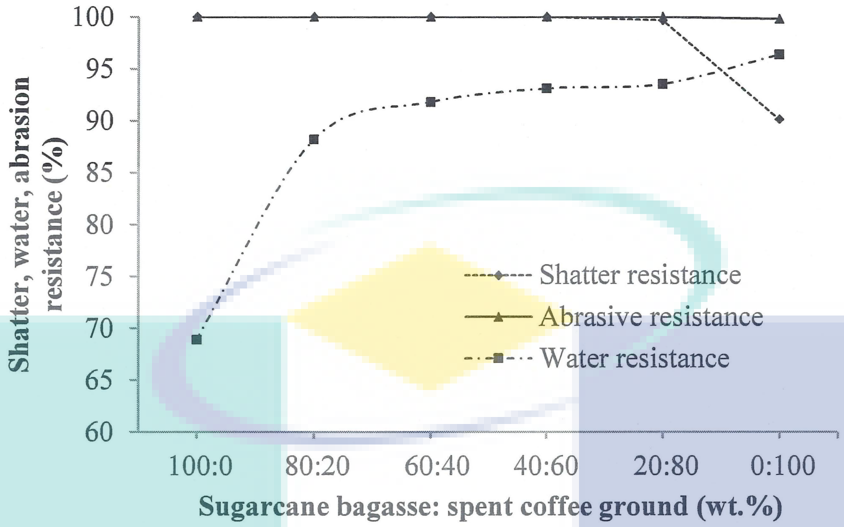


Figure 4.32 Effects of different blend ratio of sugarcane bagasse and spent coffee ground to the mechanical properties

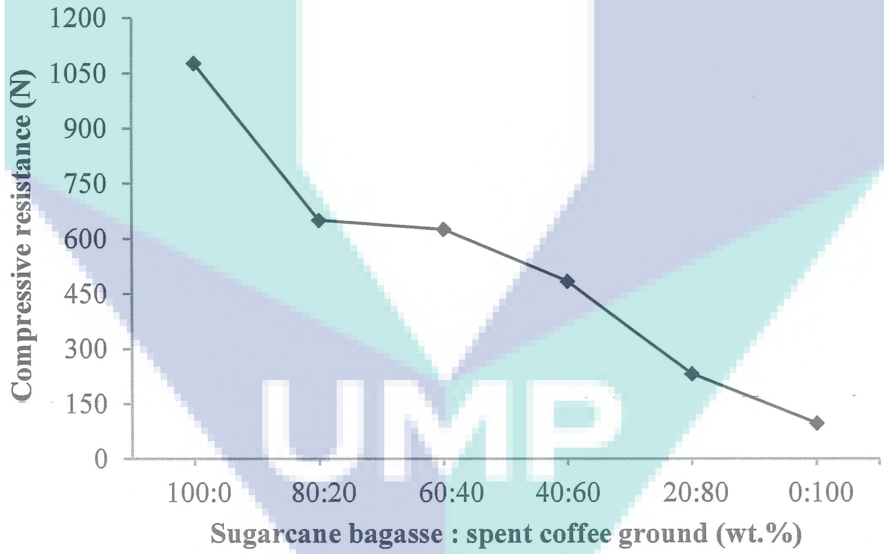
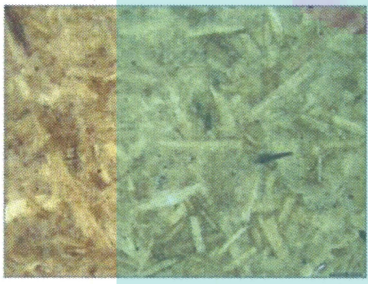
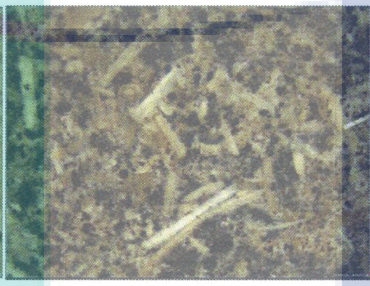


Figure 4.33 Compressive resistance for the mixture of sugarcane bagasse and spent coffee ground

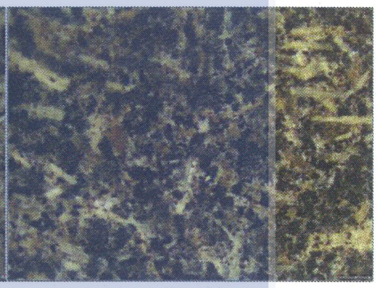
Figure 4.32 and Figure 4.33 presented a positive outcome in terms of mechanical properties resulted from the mixing of sugarcane bagasse and spent coffee ground. Briquettes from pure sugarcane bagasse had been experimentally proven to have 100% in shatter resistance and abrasive resistance, meaning that there were no fines produced when encountering the destructive forces. The briquettes remained intact after the drop test and tumbling test. This could be attributed to its fibrous structure, softer surface and lignin content. From those listed in literature, sugarcane bagasse contained about 22% of lignin (Rezende et al., 2011) which played an important role in binding. When temperature was applied during densification, the plant lignin was softened and activated, thus promoting to a better binding process. By observing the sugarcane bagasse briquette under the optical microscope with 3x, the mechanical interlocking resulted from the compaction of fibrous, flat-shaped particles (Tumuluru, Wright, Hess and Kenney, 2011) existed as shown in Figure 4.34 (i) and thus provided rigidity to the briquettes' structure.


100:0

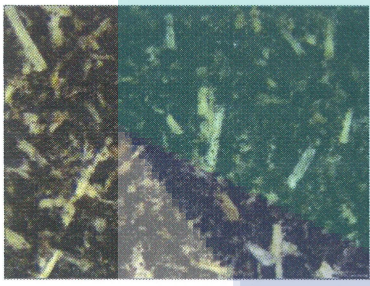
(i)


80:20

(ii)


60:40

(iii)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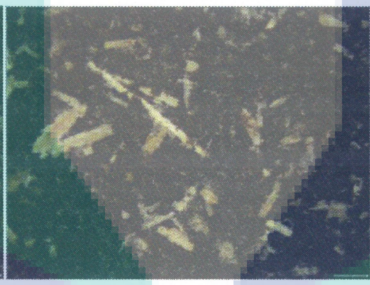
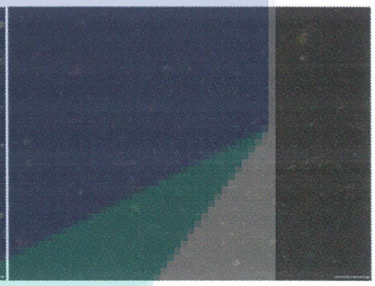
(iv)


20:80

(v)


0:100

(vi)

Figure 4.34 Microscopic images of sugarcane bagasse to spent coffee ground

On the contrary, the abrasive resistance and shatter resistance of spent coffee ground briquettes were slightly lower by 0.21% and 9.86% as compared to that of sugarcane bagasse briquette due to its lower lignin (0.05%) contents (Murthy and Madhava Naidu, 2012). When spent coffee ground was compacted, tiny voids appeared as shown in Figure 4.34 (vi). The mechanical interlocking, solid bridges and stronger binding might be absence due to the inherent nature as well as the chemical elements of spent coffee ground. Research done by Ballesteros, Teixeira and Mussatto (2014) revealed that spent coffee ground was the material with very low porosity, so the particles still could bind properly under compaction.

Mixing of sugarcane bagasse and spent coffee ground was shown to raise the quality of the briquettes. From Figure 4.34 (ii) and (iii), mechanical interlocking and smoother surfaces of the briquettes could be observed under the optical microscope. The particles binding were considerably stronger and the gaps between these two different residues were almost invisible. Therefore, from Figure 4.32, the briquettes produced from this combination achieved 100% in abrasive resistance for the entire mixing ratio. Only 0.03-0.32% of decrement was resulted in the shatter resistance of these briquettes especially when higher spent coffee ground compositions were incorporated.

For the briquette contained more spent coffee ground than sugarcane bagasse as shown in Figure 4.34 (iv) and (v), its strength will degrade gradually whereby the inter-particles bonding might be affected and the incorporation of spent coffee ground might induce the porosity to the briquette. Lesser sugarcane bagasse could be the refinement to strengthen the adjacent particles. Therefore, a decreasing trend could be observed in the shatter resistance and compressive resistance when the spent coffee ground increased.

In the case of water resistance, pure sugarcane briquettes exhibited the highest water absorption characteristics due to its hydrophobic characteristics and water holding capacity. As revealed by Ballesteros, Teixeira and Mussatto (2014), higher water holding capacity would be resulted in the material with higher total dietary fiber (cellulose, hemicellulose, lignin and etc). As listed in Table 2.2 and Table 2.4, the three main elements of the dietary fibers of sugarcane bagasse were among the highest and thus resulting to its lower water resistance value.

However with the incorporation of spent coffee ground, the water absorption capability dropped progressively as shown in Figure 4.32, resulting in higher water resistance after the immersion test. Spent coffee ground contained a relative larger amount of oil contents (15%) which were normally extracted for biodiesel production (Kondamudi, Mohapatra and Misra, 2008). In this experiment, the collected spent coffee ground was dried and directly briquetted into solid fuel without any other additional processing. Therefore, the oil contents would still available. The oil within this material would form a layer when they were in contact with water since oil was insoluble in water, and thus inhibit or slow down the water penetration in the spent coffee ground briquette.

Blending was one of the alternatives to be adopted on enabling these two residues could be used effectively in the solid fuel production. A quality biomass briquette could be produced with the mixture of sugarcane bagasse and spent coffee ground in different mixing ratio. These two residues could complement each other with respect to their inherent characteristics and generate the briquettes with satisfactory strength and durability.

4.9.2 Combustion properties analysis

The results of combustion properties achieved by the third type of biomass residues combination would be portrayed in the following sections which included high heating value, elemental compositions, power outputs, specific fuel consumption and lastly burning rate of the briquettes.

4.9.2.1 High heating value of sugarcane bagasse and spent coffee ground briquettes

The recorded value in Figure 4.35 shows that the high heating value of the briquettes is between 18.47 MJ/kg and 24.56 MJ/kg, which fulfilled the minimum requirement (>17500 J/kg) of a commercial briquette, as stated in DIN 51731.

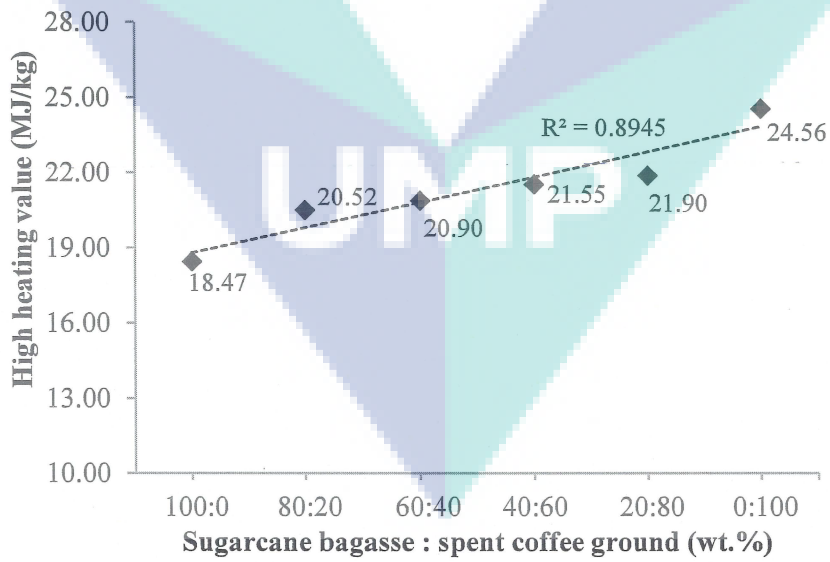


Figure 4.35 High heating value of sugarcane bagasse and spent coffee ground at different blend ratio

The calorific value of sugarcane bagasse briquettes (18.47 MJ/kg) was considered high enough, nevertheless a higher value could be resulted from the addition of spent coffee ground in the briquettes making. A positive relation (R^2= 0.8945) could be observed in Figure 4.35, where the increment of high heating value was affected by the increasing spent coffee ground in different mixing ratio. Even when only 20 wt.% of spent coffee ground was blended with 80 wt.% of sugarcane bagasse, the high heating value was increased by 2.05 MJ/kg or 11.1%. The result was consistent with the research done by Ciesielczuk, Karwaczyńska and Sporek (2015), the high heating value was 20.32 MJ/kg when 25% of spent coffee ground were blended with pure beech wood. Besides that, this type of blend briquettes could be also comparable to the low quality hard coal.

Figure 4.35 also illustrates that increasing the sugarcane bagasse content reduced the high heating value of the blend due to its lower volatile matter. It was found that sugarcane bagasse briquettes exhibited higher binding capability than the spent coffee ground, but vice versa in the case of energy value. Nonetheless, these two residues could complement each other and mix together to produce a briquette with satisfactory high heating value.

4.9.2.2 Ultimate analysis of sugarcane bagasse and spent coffee ground briquettes

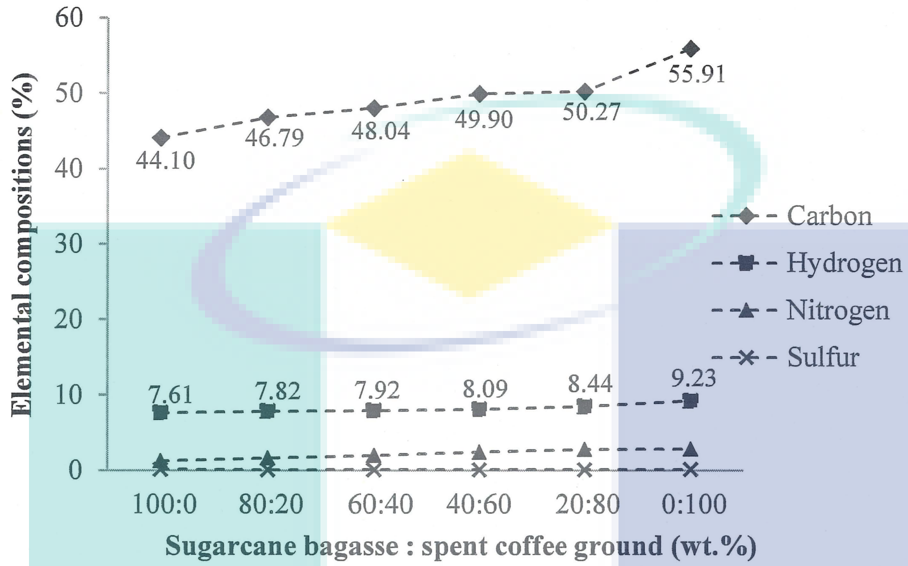


Figure 4.36 Ultimate analysis of sugarcane bagasse and spent coffee ground briquettes at different mixing ratio

As stated in literature, high heating value of a solid fuel could be estimated from its carbon and hydrogen contents. Therefore, based on the previous analysis, the spent coffee ground briquettes supposed to have higher Carbon and Hydrogen than the sugarcane bagasse briquettes and it was experimentally proven as presented in Figure 4.36. The concentrations of Carbon and Hydrogen ranged from 44.10-55.91% and 7.61-9.23% respectively, increasing as more spent coffee ground was added. The higher Carbon and Hydrogen contents of these briquettes would then positively influence the combustion efficiency.

Apart from that, the Nitrogen composition of the blend briquette was between 1.26% (sugarcane bagasse) and 2.84% (spent coffee ground). These values were considerably higher as compared to the values obtained from the previous mixture; however the Nitrogen oxidation could be controlled by maintaining the reaction temperature during combustion (Forero-Nuñez, Jochum and Sierra, 2015). In the case of Sulphur content, the values obtained by the briquettes made from sugarcane bagasse and spent coffee ground were 0.124% and 0.13% respectively, which were slightly higher than 0.1%. Surprisingly, it was found that the Sulphur content of the blend briquettes was less than 0.1%, ranging from 0.078-0.098%. The lower Sulphur content indicated that these blend briquettes were eco-friendly and could be used in the application for the heat and energy generation. As revealed by Rezania et al. (2016), a good quality biomass briquette would bring beneficial impacts for the environment.

4.9.2.3 Results from water boiling test of sugarcane bagasse and spent coffee ground briquettes

The results obtained from the water boiling test were used to calculate the specific fuel consumption, burning rate and power outputs as shown in Figure 4.37, Figure 4.38 and Figure 4.39, respectively.

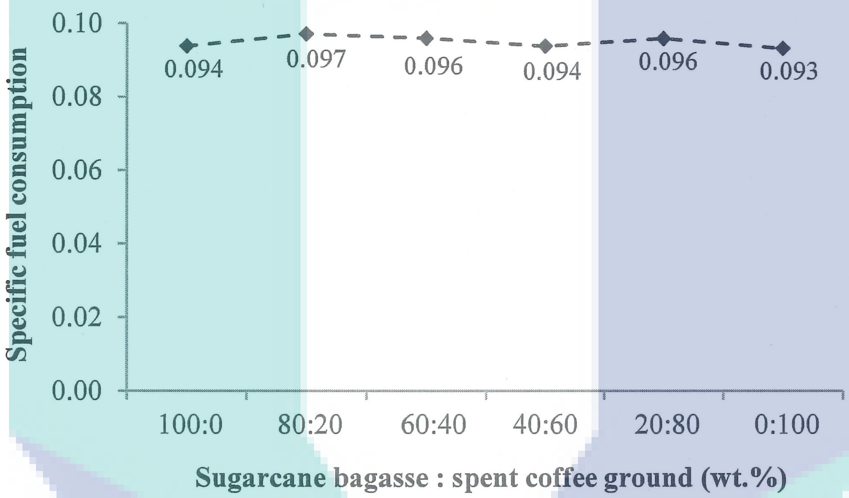


Figure 4.37 Effect of mixing ratio to specific fuel consumption of rice husk-spent coffee ground briquettes

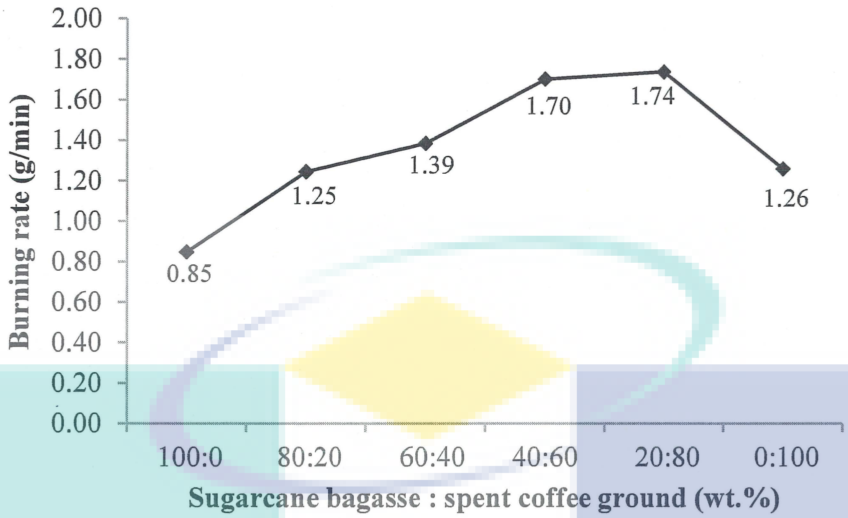


Figure 4.38 Burning rate of sugarcane bagasse and spent coffee ground mixture at varying blend ratio

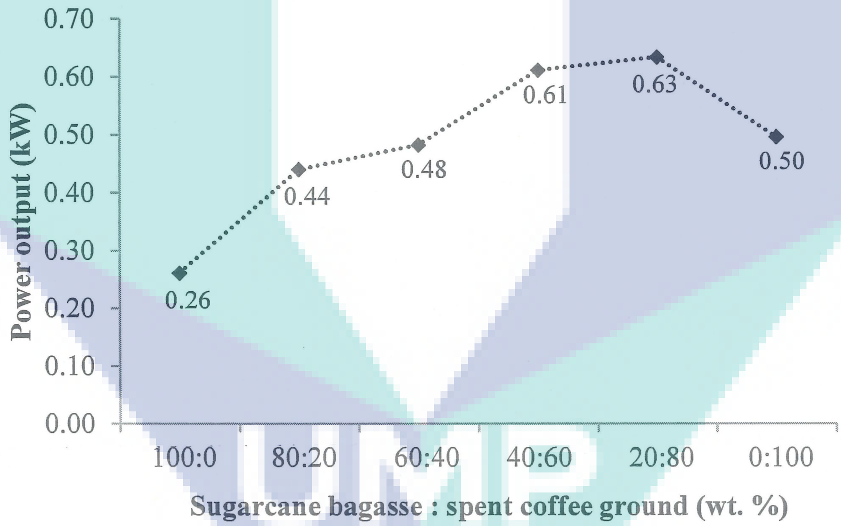


Figure 4.39 Effect of mixing ratio to power output of the briquette with sugarcane bagasse and spent coffee ground

The burning performance of the briquettes formed with sugarcane bagasse and spent coffee ground was better than the previous combinations. The burning of all these briquettes could boil the water at 100°C. Figure 4.37 illustrates the trend plot of specific fuel consumption with respect to different mixing ratio of sugarcane bagasse to spent coffee ground, ranging from 0.093 to 0.097 kg of fuel/ kg of water. The changes on values recorded for each mixing ratio was insignificant, meaning that almost equal amount of fuel from different mixing ratio was required to boil 1 kg of water.

As observed from Figure 4.38 and Figure 4.39, briquettes formed at the mixing ratio 20:80 of sugarcane bagasse to spent coffee ground exhibited the highest burning rate (1.74 g/min) and power output (0.63 kW). Besides that, the values recorded for the blend briquettes (40:60) and (20:80) were higher than that of the spent coffee ground briquettes. This could be explained by referring to their water boiling time whereby these two blend briquettes required shorter time to boil the water as compared to the usage of spent coffee ground briquettes. As revealed by Onuegbu et al. (2011), burning rate of the briquette would control its water boiling time. This meant that blend briquettes were able to boil water faster than the pure spent coffee ground briquette and resulted in faster burning rate during combustion.

A list of summary on the mechanical properties and combustion properties of the respective blend ratio for each combination was clearly portrayed in Table 4.13.

Table 4.13 Summary of mechanical properties, combustion properties and optimum blend ratio for three combinations

Property	**Rice husk: Sugarcane bagasse**	**Rice husk : spent coffee ground**	**Sugarcane bagasse : spent coffee ground**	**Reference / requirement**
Optimum blend ratio	20:80	20:80	40:60	-
Mechanical property				
Shatter resistance (%)	100.00	95.58	99.97	90.00
Abrasive resistance (%)	100.00	99.86	100.00	95.00
Water resistance (%)	84.87	94.92	93.12	95.00
Compressive resistance (N)	709.55	185.04	484.59	-
Combustion property				
High heating value (MJ/kg)	17.85	21.28	21.55	17.50
Carbon (%)	42.95	48.86	50.27	-
Hydrogen (%)	7.37	8.03	8.44	-
Nitrogen (%)	0.60	2.83	2.82	-
Sulphur (%)	0.06	0.09	0.10	< 0.10
Power outputs (kW)	0.26	0.50	0.61	-
Specific fuel consumption (kg of fuel/ kg of water)	0.10	0.09	0.09	-
Burning rate (g/min)	0.87	1.42	1.70	-

4.10 Summary

Mechanical properties and combustion properties are two main concerns to decide the quality of a solid fuel in order to be used efficiently for energy generation. In conjunction with the aim of the project, the first set of experiment was conducted to investigate the optimum condition by evaluating the effect of temperature and pressure on the mechanical properties of the briquettes produced from three residues individually. As a result, it was observed that there was a positive effect of increasing temperature and pressure on the mechanical properties of the briquettes formed from each residue individually. On top of that, the optimum temperature and pressure resulted from the analysis was 150°C, 300 bars in which most of the briquettes could fulfil the acceptance limit.

For the second set of experiment, briquettes formed with different blend ratio of residues were formed and the fuel properties were evaluated in terms of mechanical properties and combustion properties as well. At the end of the research, the optimum blend ratio from each combination had been selected.

CHAPTER 5

CONCLUSION

5.1 Conclusion

The overall objective of the research was achieved in which the potential of the selected agricultural biomass to be converted into quality solid fuel has been investigated through a series of implemented methods and analyses. The two research objectives were achieved through two different stages of experiments, respectively:

a. The effect of compacting pressure and preheating temperature on the mechanical properties of the briquettes formed from pure residues had been analysed and consequently the optimum temperature and pressure could be selected.
b. The effect of mixing of two types of residues in different blend ratio on the mechanical and combustion properties of the final briquettes.

The analyses in the first stage of experiment were conducted to fulfil objective one (a). From this first stage of experiment, the briquettes produced from rice husk, sugarcane bagasse and spent coffee ground could sustain in shape after being extracted from the mold. Besides, increasing of preheating temperature and compacting pressure were proven to enhance the mechanical strength and durability of the briquettes and most of the briquettes could achieve the acceptance limit for each analysis. Also, the result showed that the individual residue owned their respective strengths and weaknesses for each type of biomass feedstock. Sugarcane bagasse had the fibrous structure, higher binding capability and thus contributing to its higher mechanical strength. However, the water resistance of the sugarcane bagasse was relatively lower in which the briquettes would disintegrate easily when they are exposed to water or rain. Spent coffee ground briquettes, on the other hand, showed the lower mechanical strength due to the limited amount of lignin, but the inherent nature of this material itself had contributed to the higher water resistance. Briquetting of biomass blend enabled the residues to complement each other with respect to their strengths and weaknesses and thus improving the fuel properties of the final briquettes in terms of mechanical strength, durability and combustion characteristics.

Through the second stage of experiment, the second objective (b) was achieved. Three different types of blend briquettes were produced at the optimum temperature and pressure decided from the analysis done previously. The mechanical and combustion properties of each type of blend briquettes were analysed with respect to the blend ratio (20:80, 40:60, 60:40, 80:20), including the pure residue briquettes with the denotation of 100:0 and 0:100. It was found that the results obtained in this stage corresponded well with those stated in the literature and hypothesis in which mixing of biomass materials could help to improve the mechanical strength and durability, high heating value, elemental compositions, specific fuel consumption, power output as well as burning rate of the densified biomass products. Also, the optimum blend ratio for each biomass combination selected from the analyses are as follows; rice husk to sugarcane bagasse (20:80), rice husk to spent coffee ground (20:80) and sugarcane bagasse to spent coffee ground (40:60). These blend briquettes were able to fulfil the minimum requirement of the mechanical strength, durability, calorific value as well as satisfactory combustion rate as a commercial briquettes.

5.2 Future works

Three suggestions are proposed as follows for future work:

a. Similar methodologies adopted in this research could be referred and applied for the briquetting of other biomass residues. Due to the seasonal variations, the availability of agricultural biomass feedstock might be affected. Therefore, research could be conducted to study the suitability and how the other residues could be used to produce solid fuel. The results might be different owing to the inherent nature of the residues.

b. The summary of the research findings is served as a technical guideline for biomass briquette development especially for biomass blending. Mixing of different biomass materials that replace the usage of binder to enhance the binding of briquettes could be one of the alternative solutions for the industry other than depending on the palm waste and wood residues in solid fuel formation for energy generation. These briquettes could be used in the application of combustion and gasification.

c. In order to ensure a sustainable and continuous production of briquettes, several improvements need to be done on the briquetting facility. It is suggested that the hydraulic press can be designed as automated instead of manually operated in order to increase productivity. Besides, heat insulation could be added in the briquetting facility since it was not incorporated in this research study, particularly the heating section in order to slow down the heat release during briquetting process, and thus additional cost for heating could be reduced.

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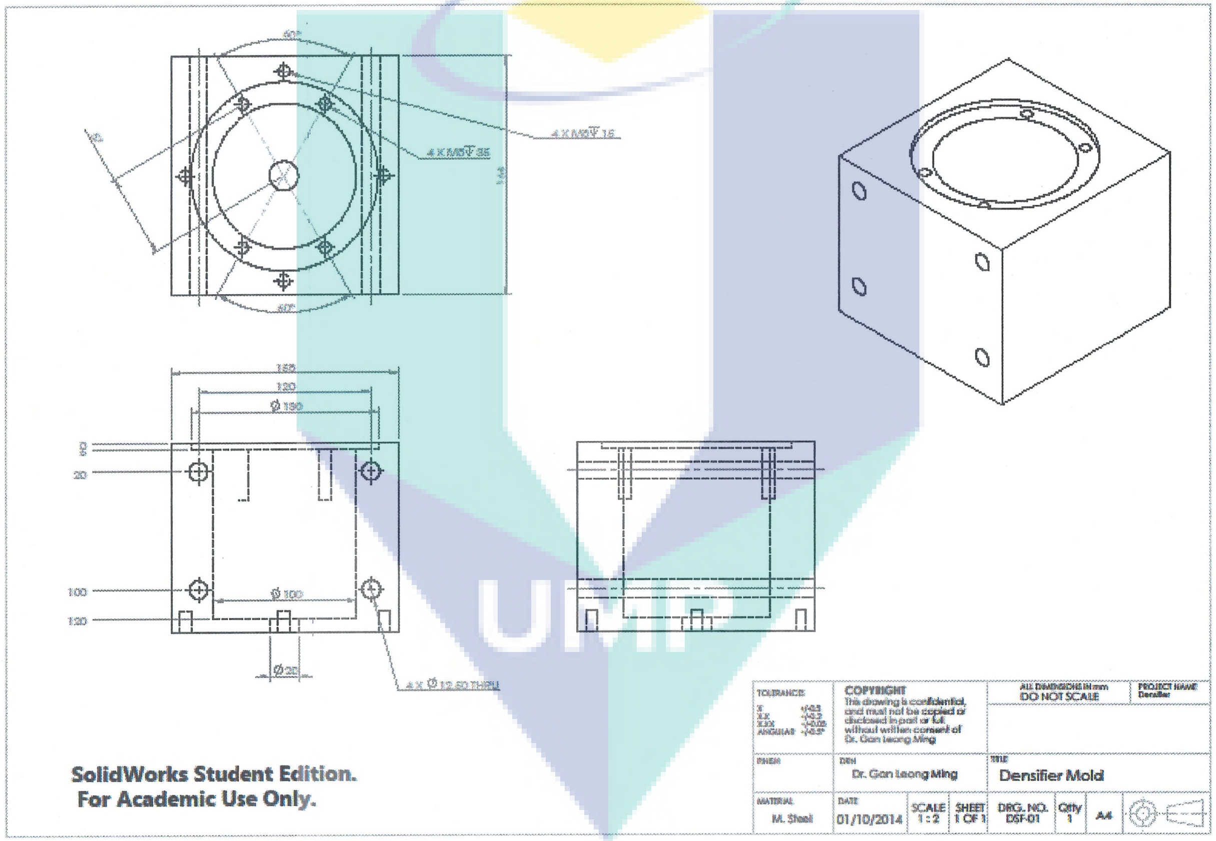
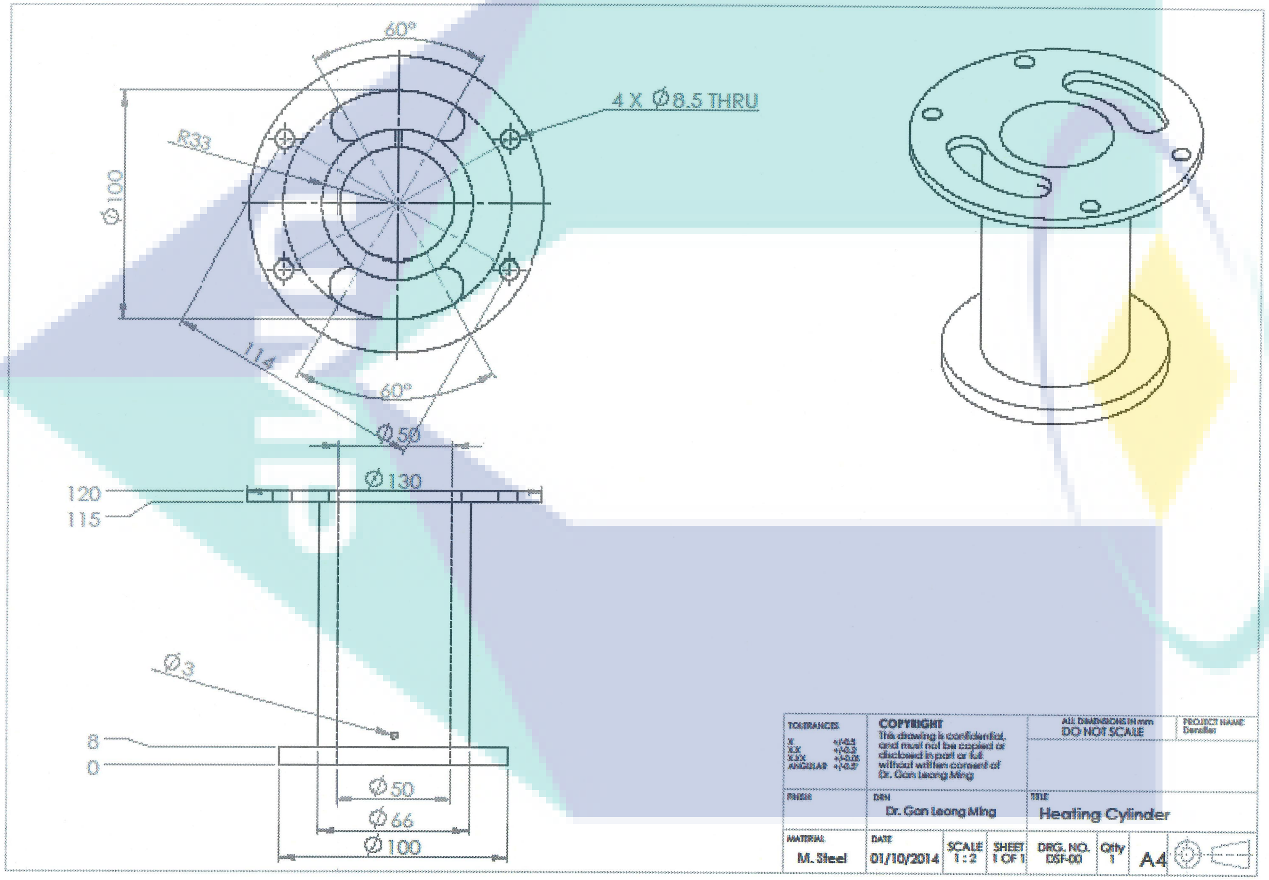
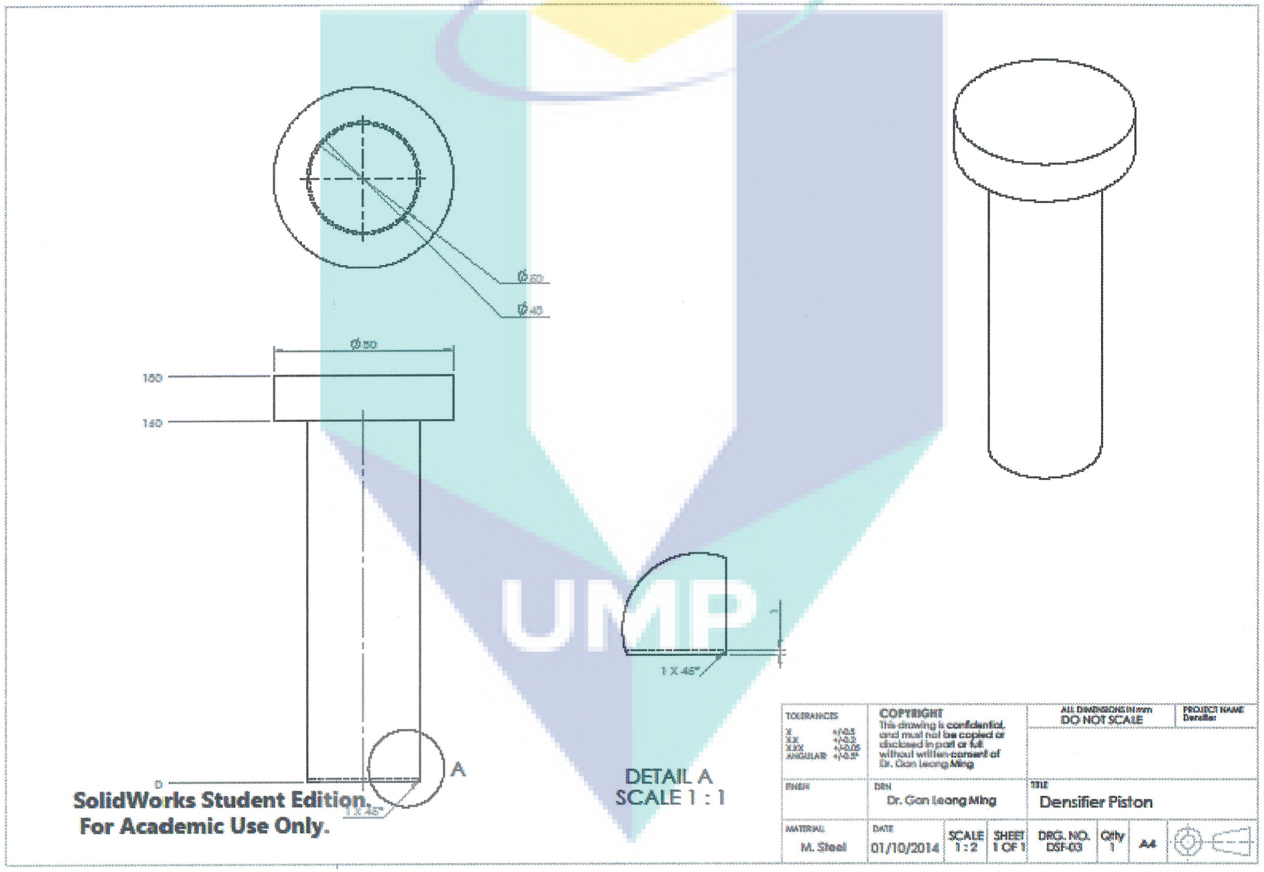
APPENDIX A1
DENSIFIER MOLD



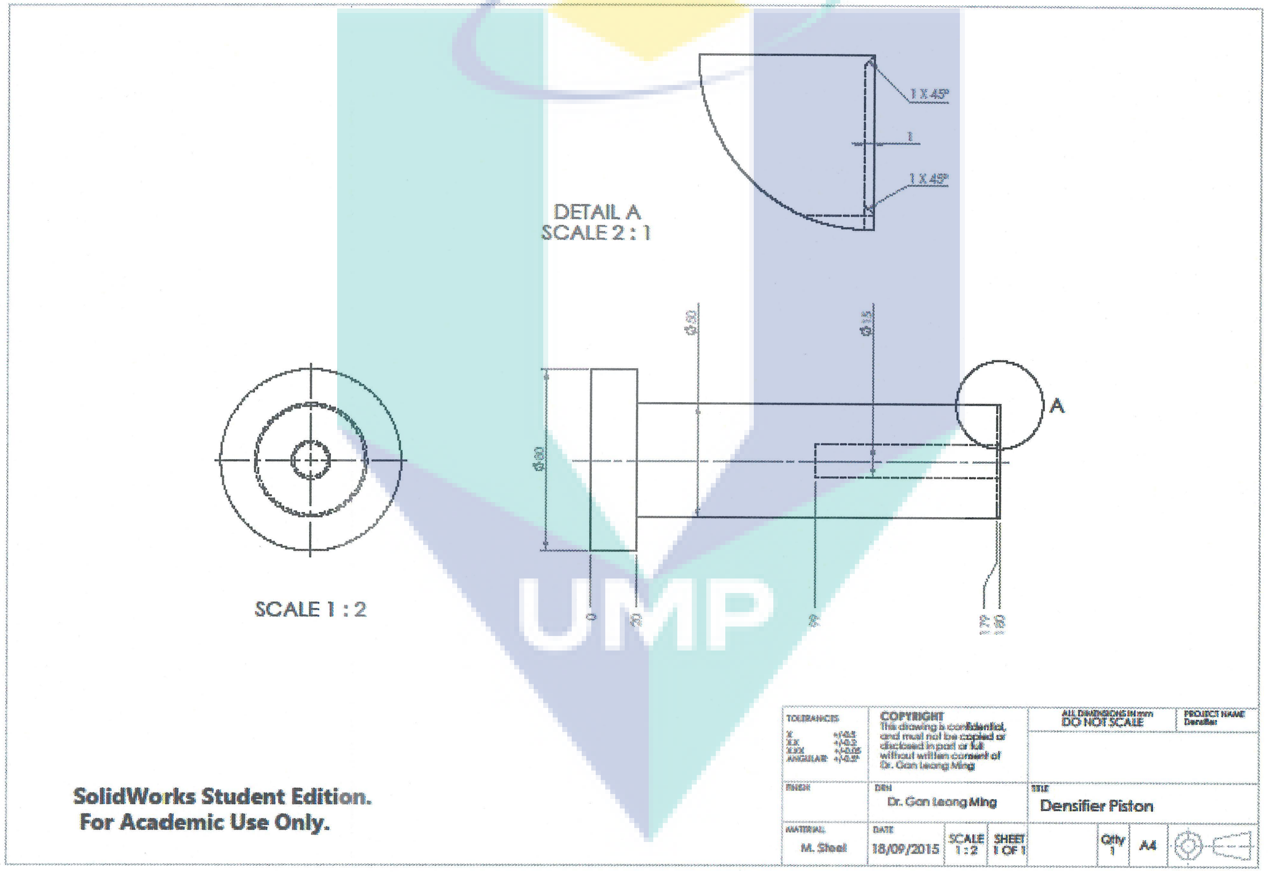
APPENDIX A2
HEATING CYLINDER



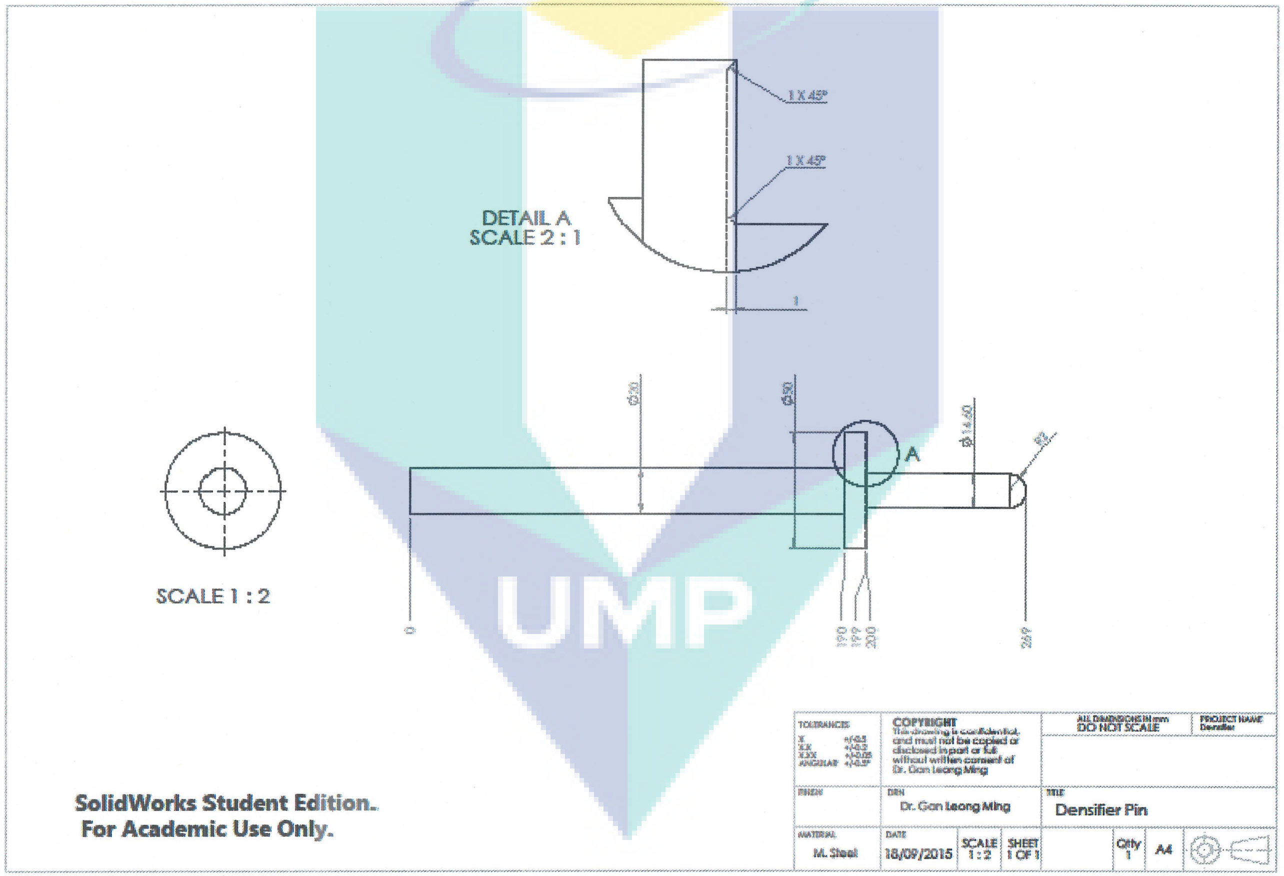
APPENDIX A3
DENSIFIER PISTON (1)



APPENDIX A5
DENSIFIER PISTON (2)



APPENDIX A6
BACKSTOP PIN (2)



APPENDIX B
STANDARD OPERATING PROCEDURE OF USING BOMB CALORIMETER

1. A combustion capsule was clened and dried using a cloth and less than 1g of sample was weighed using an analytical balanace.
2. The sample was filled inside the combustion capsule.
3. The combustion capsule was then fixed on the bomb head.
4. 10 cm of fuse wire was cut accordingly. Then, the fuse wire was attached on the bomb head by raising the cap and inserting the wire through the eyelet, a 'U' shape was made and the cap was pulled downward to fix the wire in position.
5. The fuse wire must touch the sample but should not touch the combustion capsule to prevent short circuit.
6. Then, the bomb head with the capsule was carefully lifted and attached to the combustion bomb by locking using the screw cap until it was tight.
7. The bomb was filled with oxygen gas at around 30 atm. The filling connection control valve was first untightened before filling with oxygen. After the oxygen was supplied to the bomb, the control valve was closed; the oxygen was continuously filled until the pressure gauge showed 30 atm.
8. The oval bucket was filled with 2 L of distilled water and placed into the jacket.
9. The lifting handle was attached to the two holes at the side of the screw cap and the combustion bomb was lowered vertically into the water. The combustion bomb must be handled carefully for not disturbing the sample. It was important to ensure that there were no bubbles/ leaking from combustion bomb.
10. The handle was then removed from the bomb.
11. The ignition lead wires were connected to the terminal sockets on the bomb.
12. The cover was put vertically on the jacket with the stirrer and thermometer facing toward the front. The stirrer was turned by hand to be sure that it ran freely. After that, the drive belt was slipped onto the pulleys and the motor was started.
13. After the apparatus was set up, there was few setting on the calorimetric thermometer which was able to provide automatic control and communication capabilities to the jacket calorimeter.
14. The calorimeter operation was selected from the touch screen, followed by switching on the stirrer. After that, the 'start' pad was pressed and the ID of the sample as well as the weight of the sample was keyed in.

15. The experiment required around 14 to 15 minutes for one sample if there was none of misfire condition occurring.
16. Once the slip with the value of gross calorific value was printed out, the experiment ended. The motor was stopped, the belt was removed and also the cover was lifted from the calorimeter vertically and put on the support stand.

APPENDIX C1
RICE HUSK BRIQUETTES

Preheating temperature (° C)	Compacting pressure (bar)	Rice husk briquette
120	200	
	250	
	300	
150	200	
	250	

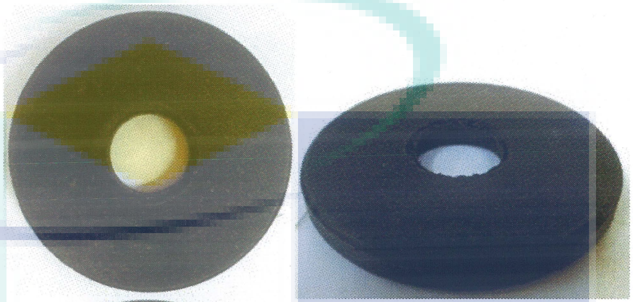
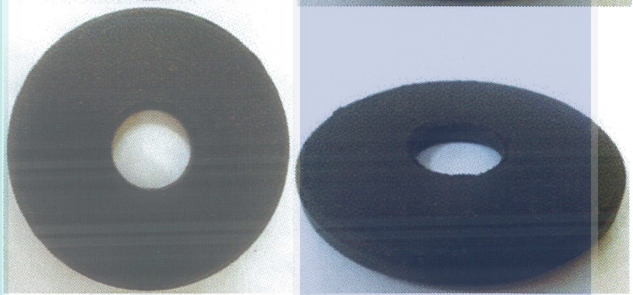
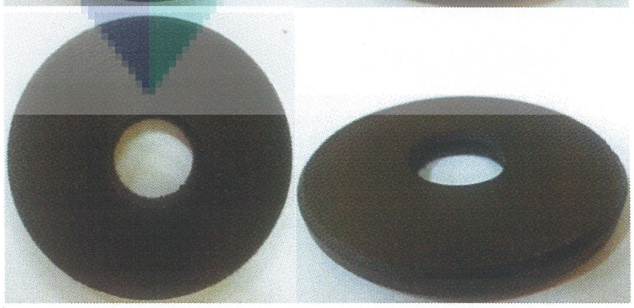
	300	
180	200	
	250	
	300	

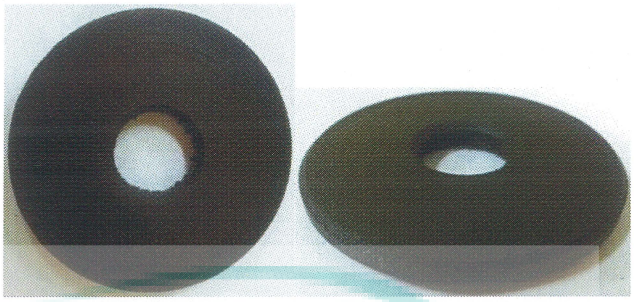
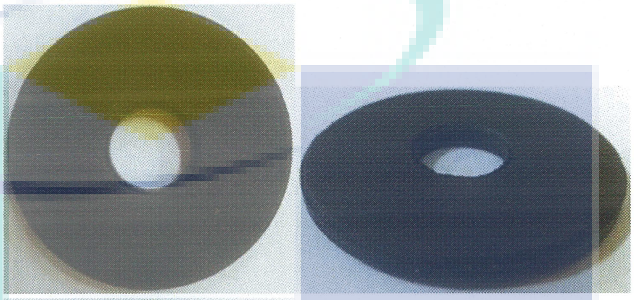
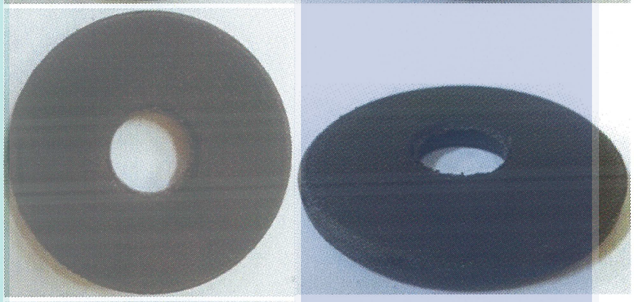
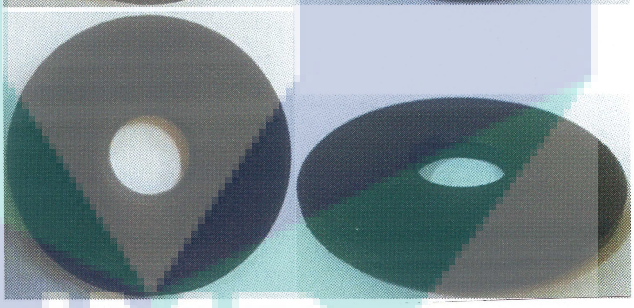
APPENDIX C2
SUGARCANE BAGASSE BRIQUETTES

Preheating temperature (° C)	Compacting pressure (bar)	Sugarcane bagasse briquette	
120	200		
	250		
	300		
150	200		
	250		

	300	
	200	
180	250	
	300	

APPENDIX C3
SPENT COFFEE GROUND BRIQUETTES

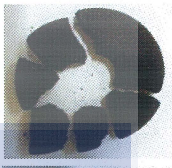
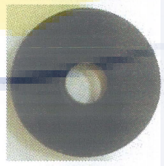
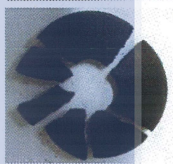
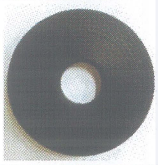
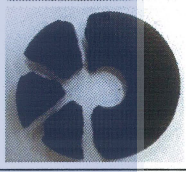
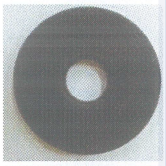
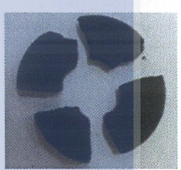
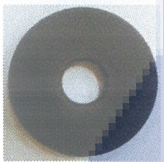
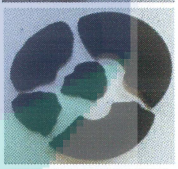
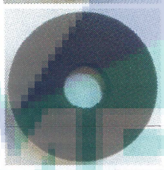
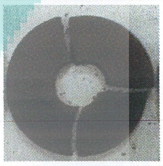
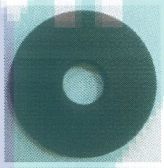
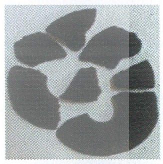
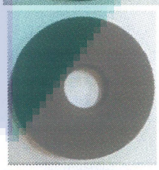
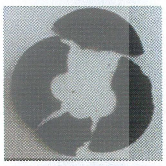
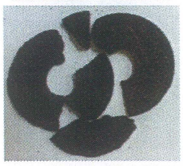
Pre-heating temperature (° C)	Compacting pressure (bar)	Spend coffee ground briquette
120	200	
	250	
	300	
150	200	
	250	

	300	
180	200	
	250	
	300	

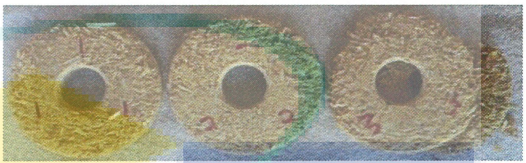
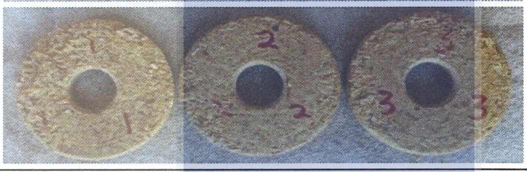
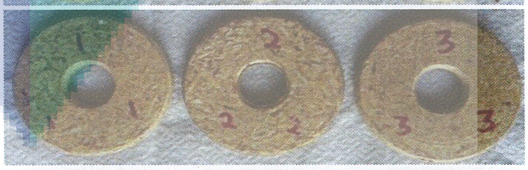
APPENDIX D1
SHATTER RESISTANCE TEST (RICE HUSK BRIQUETTES)

Preheating temperature (°C)	Compacting pressure (bar)	Before shattering	After shattering
120	200		
	250		
	300		
150	200		
	250		
	300		
180	200		
	250		
	300		

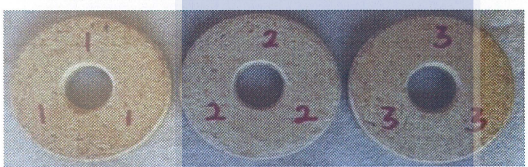
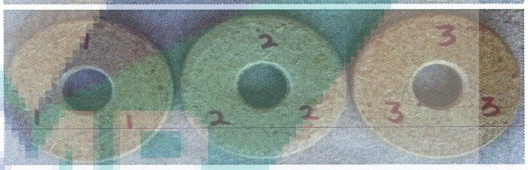
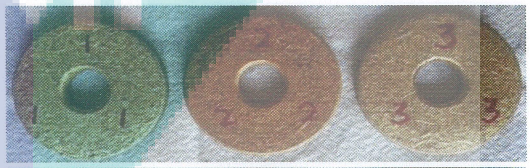
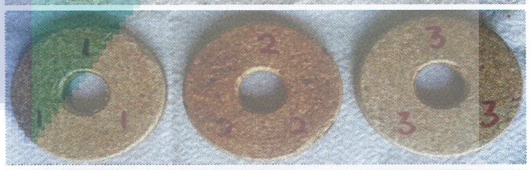
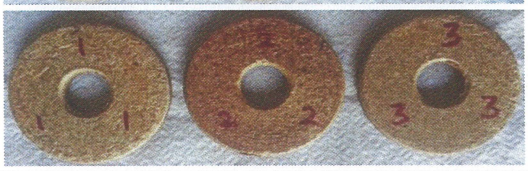
APPENDIX D3
SHATTER RESISTANCE TEST (SPENT COFFEE GROUND BRIQUETTES)

Preheating temperature (°C)	Compacting pressure (bar)	Before shattering	After shattering
120	200		
	250		
	300		
150	200		
	250		
	300		
180	200		
	250		
	300		

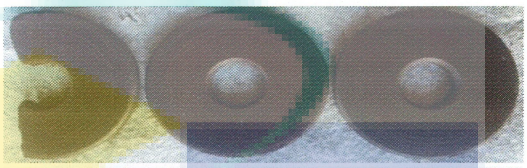
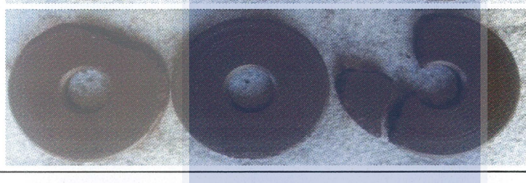
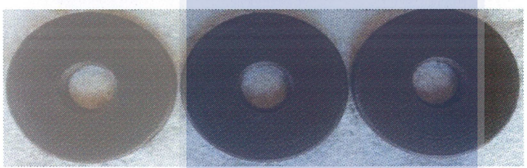
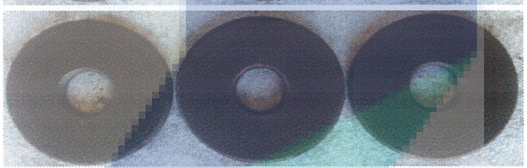
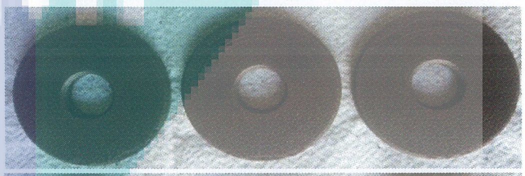
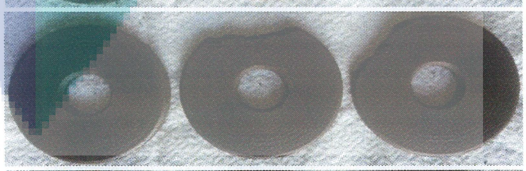
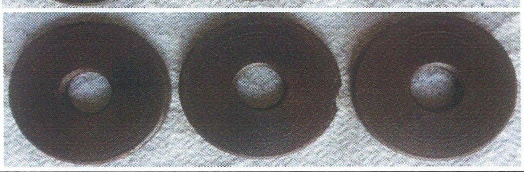
APPENDIX E1
ABRASIVE RESISTANCE TEST (RICE HUSK BRIQUETTES)

Preheating temperature (^oC)	Compacting pressure (bar)	After tumbling test
120	200	
	250	
	300	
150	200	
	250	
	300	
180	200	
	250	
	300	

APPENDIX E2
ABRASIVE RESISTANCE TEST (SUGARCANE BAGASSE BRIQUETTES)

Preheating temperature (°C)	Compacting pressure (bar)	After tumbling test
120	200	
	250	
	300	
150	200	
	250	
	300	
180	200	
	250	
	300	

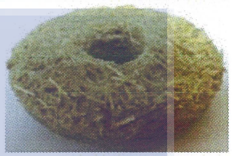
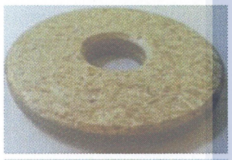
APPENDIX E3
ABRASIVE RESISTANCE TEST (SPENT COFFEE GROUND BRIQUETTES)

Preheating temperature (°C)	Compacting pressure (bar)	After tumbling test
120	200	
	250	
	300	
150	200	
	250	
	300	
180	200	
	250	
	300	

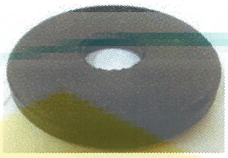
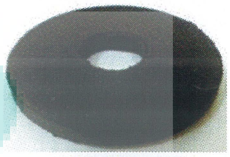
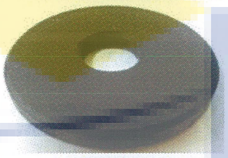
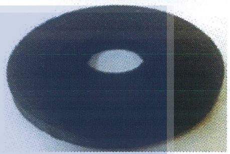
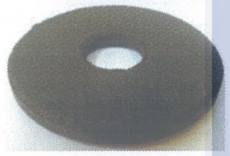
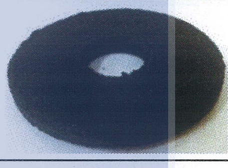
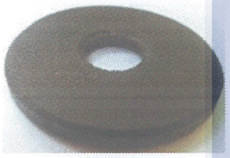
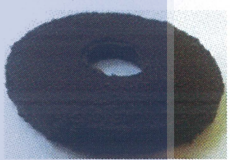
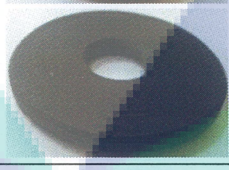
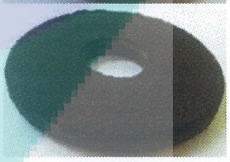
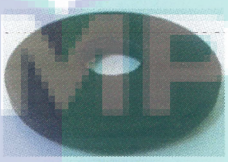
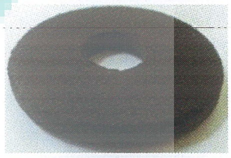
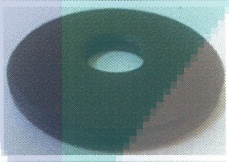
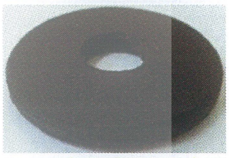
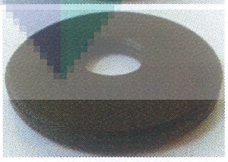
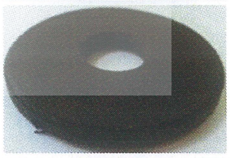
APPENDIX F1
WATER RESISTANCE TEST (RICE HUSK BRIQUETTES)

Preheating temperature (°C)	Compacting pressure (bar)	Before immersion	After immersion
120	200		
	250		
	300		
150	200		
	250		
	300		
180	200		
	250		
	300		

APPENDIX F2
IMMERSION TEST (SUGARCANE BAGASSE BRIQUETTES)

Preheating temperature (°C)	Compacting pressure (bar)	Before immersion	After immersion
120	200		
	250		
	300		
150	200		
	250		
	300		
180	200		
	250		
	300		

APPENDIX F3
WATER RESISTANCE TEST (SPENT COFFEE GROUND BRIQUETTES)

Preheating temperature (ºC)	Compacting pressure (bar)	Before immersion	After immersion
120	200		
	250		
	300		
150	200		
	250		
	300		
180	200		
	250		
	300		

LIST OF PUBLICATIONS

Gan, Leong Ming, Law, Hoon Chit and R.A., Bakar (2015) *Development of a Briquetting Facility with the integration of a Hydraulic System for Biomass Densification*. Energy and Sustainability V: Special Contributions, 206. pp. 335-345. ISSN 1743-3541. Item availability resitricted.

Gan, Leong Ming, Gan, Hui Leng and Law, Hoon Chit (2015) *Analysis on the Grinding Quality of Palm Oil Fibers by Using a Combined Grinding Equipment*. In: IOP Conference Series: Materials Science and Engineering, 3rd International Conference on Mechanical Engineering Research (ICMER 2015), 18-19 August 2015, Kuantan, Pahang. pp. 1-8., 100 (012047). Item availability restricted.

Law, Hoon Chit, Gan, Leong Ming and Gan, Hui Leng (2016) *Experimental Study on the Mechanical Properties of Biomass Briquette from Different Agricultural Residues Combination*. MATEC Web Conference (Publication pending)